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EFFECT OF SURFACE AREA AND THICKNESS ON FIRE LOADS

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ABSTRACT

The report reviews the effect of surface area and thickness of fire loads in predicting the value of the heat release rate. The investigation arises from current Ph. D research at the University of Canterbury identifying the need for fire load data, which also includes the exposed surface area of the fuel items, so that the rate and duration of burning can be better assessed, especially during post-flashover fires. This is because at some stage of the fire, the fuel is no longer dependent on the ventilation characteristics but the surface area exposed to the fire.

The investigation of the effect of surface and thickness on fire load is first carried out with the burning of single items, such as furniture normally found in each building occupancy. Later, fire load surveys on a range of typical building occupancies, such as university offices, motels and residential are conducted. Simple models for calculating the surface area of the fire load, especially for wood and plastic materials have been determined.

Based on the methodology developed for the investigation, it is found that the larger the exposure of the fuel surface area to the fire, the higher the heat release rate, and the thicker the fuel, the longer the duration of burning. In other words, the value of the heat release rate is a function of the surface area, while the duration of burning is a function of the thickness of the fuel. Burning behaviour of the fire load inside a fire compartment during a post-flashover fire, based on the exposed surface to the fire is also presumed.

Previous fire load surveys conducted are also included for comparisons of the results.

Recommendations for future study of the effect of the surface area and thickness on fire loads during a fire are provided.

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A	surface area exposed to the fire (m^2)
A_B, A_v	area of the window (m^2)
A_f	total floor area (m^2)
A_p	thermoplastic pool area exposed to fire (m^2)
A_t	total internal surface area (m^2)
B	total fire loading (kg)
b	unit fire loading (kg/m^2)
C_3	factor used for wood, metal or plastic frames
D	thickness of stick/slab or wood fuel (m)
D_p	thickness of thermoplastic pool surface (m)
D_s	depth of the surface exposed to the fire (m)
D_{sp}	diameter of sphere (m)
d	diameter of the pool (m)
E1	energy released beyond the ventilation limit (MJ)
E2	energy released under the ventilation limit (MJ)
F_v	total ventilation factor ($m^{5/2}$)
f_v	unit ventilation factor ($m^{3/2}$)
H, H_v	height of the window (m)
HRR	Heat Release Rate (MW)
H_t	height of the fire compartment (m)
L	length of the fire compartment (m)
L_v	heat of gasification (kJ/kg)
M_v	total weight of each combustible item (kg)
m	mass of fuel item (kg)
m'', $\dot{m}''$	mass loss rate per unit area ($kg/s.m^2$)
m_c	moisture content as percentage by weight of wood
m_d	moisture content as a percentage of the dry weight of wood
n	a constant number
n^2	number of sticks required
Q	fuel surface controlled heat release rate (MW)
Q_{vent}	ventilation controlled heat release rate (MW)
q	fire load per unit total surface area (MJ/m^2)

$\dot{q}_{fs}$	peak full-scale heat release rate (MW)
$\dot{q}_i$	net heat flux (kW/m^2)
R	mass loss rate (kg/s)
r	unit burn rates (kg/s.m^2)
S	centre to centre spacing (mm)
s	standard deviation
t	time exposed (s)
t_b	duration of burning of thermoplastic material predicted by the triangular shape model (s)
t_d	duration of burning (s)
t_e	equivalent period (min)
t_f	fire resistance (min)
t_h	duration (hrs)
t_m	duration (mins)
t_s	duration (secs)
V	volume of fuel item (m^3)
vs.	versus
W	width of the fire compartment (m)
W_s	width of the surface exposed to the fire (m)
X	mean
ΔH_c	net calorific value (MJ/kg)
$\Delta H_{c,d}$	heat of combustion of oven dry wood (MJ/kg)
Δh_c	effective heat of combustion (MJ/kg)
Σ	sum
α	fire load density (kg/m^2 or MJ/m^2)
β	constant indicating how many sides of the width or depth of the surface are being regressed in the fire
γ	fire load per unit area of ventilation (kg/m^2 or MJ/m^2)
v_p	regression rate (m/s)
π	pi = 3.142
ρ	density (kg/m^3)
τ	thickness of fuel being burned with time (m)

Types of fuel:

E	electrical
G	glass
P	plastic
S	steel
W	wood

1. INTRODUCTION

Fires within buildings are complex events and are recognized as one of the major threats to life and property in many countries. As stated in the Approved Documents in New Zealand (BIA, 1992), the primary goal of fire protection is to limit, to acceptable levels, the probability of death, injury, and property loss in an unwanted fire. Therefore, it is paramount to provide adequate fire safety and protection in buildings.

Fire development in any room without any intervention can be divided into three periods: the growth period, the full development period, and the decay period, as shown in Figure 1.1.

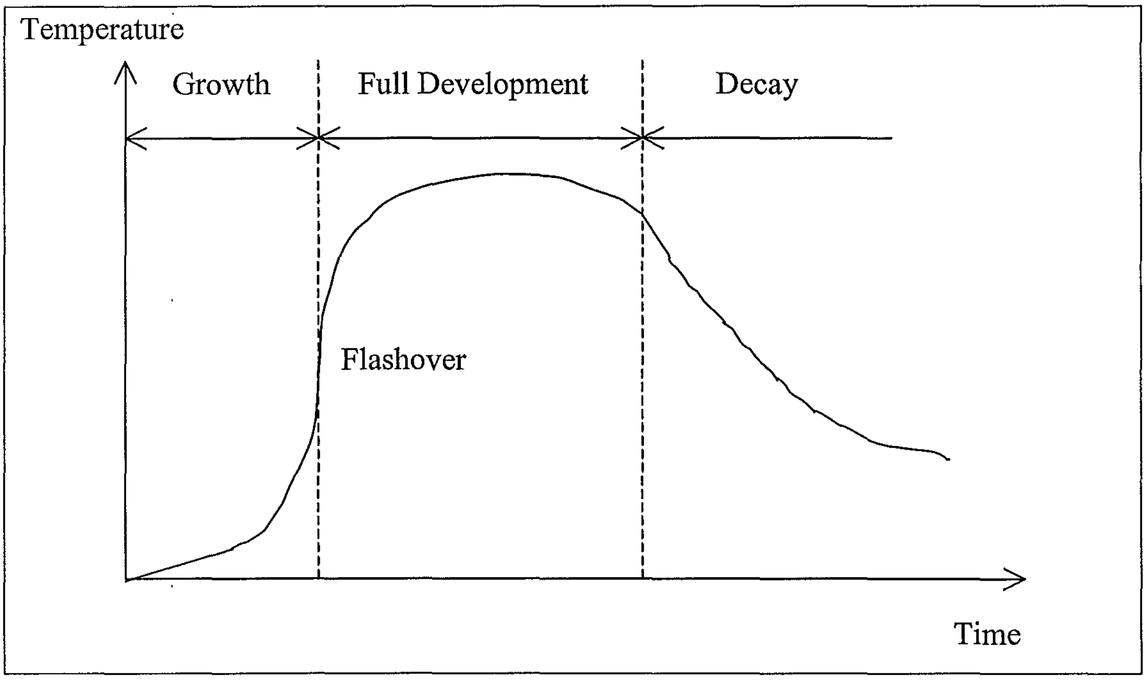


Figure 1.1: Time temperature curve for full process of fire development in a compartment without any intervention.

In the growth period, the intensity of fire increases as more and more of the combustible surfaces become involved. During this period, the rate of burning is generally controlled by the nature of the burning fuel surfaces. When the upper layer temperatures reach about 600°C, the fire reaches a full development period, which is also known as "full room involvement", after flashover. In this stage, all the combustible materials in the room begin burning actively, and the temperature rises sharply. Although generally during this period the rate of burning is governed by the available ventilation, it may sometimes be controlled by the surface area of the fuel. This happens especially in large well ventilated rooms, where the rate of burning will be similar to that which would occur for the fuel load burning in the open air. In the decay period, most fires become fuel controlled.

Risk of failure begins with the onset of post flashover fire period where the threats to structural survival become imminent. Therefore, this report will focus mainly on the fire severity during post-flashover conditions.

In order to withstand the destruction caused during the fire, it is usually assumed that the fire resistance of the room containing the fire must be such as to survive complete burnout of the fire load. Because the expected fire severity is one of the bases for the fire resistance requirements of structures, knowledge of it is essential. At present, predictions of fire severities can be made as a function of the amount of combustible materials present in the room, the size and geometry of the room, the dimensions of the ventilation available, the heat losses to the surroundings, the emissivity of the flames in the room and the thermal properties of the room surfaces.

However, in predicting the fire performance, two critical parameters, which are the fire load and the ventilation characteristics of the room, must be known. Besides the ventilation characteristics, fire load is the starting point for estimating the potential size and severity of a fire. Previous surveys have measured only mass and calorific value of the fuel load. However, at present, a need has been identified for fuel load data, which also includes the exposed surface area of the fuel items, so that the rate and duration of fuel controlled burning can be better assessed. The intensity and duration of fire in different building occupancies varies greatly depending on the amount and surface area of the combustible material present, as well as the characteristics of the available ventilation. Therefore, an accurate prediction of the possible fire load in a certain building occupancy will assist the engineer to better estimate the likely fire severity, and thus help to provide adequate and cost-effective fire protection.

This report presents a brief review of the previous surveys done by others in Chapter 2. It outlines the work carried out in surveying the fire load for different types of building occupancies such as motels, hotels, offices, restaurants, hospitals, and domestic houses.

The assumptions and theory of the burning rate and the burning behaviour of different type of fire loads, mainly solid wood fuel, and thermoplastic materials are discussed in Chapter 3. Chapter 4 reviews the effects of fuel surface area on the heat release rate of the fire load with simple geometry, such as sticks (wood cribs), cubes, spheres and other plastic materials. Effect of ventilation controlled heat released rate is briefly introduced and discussed in Chapter 5. More complex items of furniture are measured carefully and accurately to obtain their surface area. These data are used to predict the duration of burning and heat release rate of furniture due to the surface area exposed to fire, and this is detailed in Chapter 6.

Development of a procedure for conducting a fire load survey in typical building occupancies is presented in Chapter 7, and the analysis of the results and the comparison with previous results are reviewed in Chapter 8.

Conclusions, including recommendations for more a appropriate model in predicting the heat release rate of fire load due to its surface area being exposed to fire are proposed in Chapter 9.

2. LITERATURE SURVEY

2.1 Definition of Fire Load

Fire load is the starting point for estimating the potential size and severity of a fire, and thus the endurance required of walls, columns, doors, floor-ceiling assemblies and other parts of the enclosing compartment. The term "fire load" is defined as the total heat content upon complete combustion of all the combustible material contained inside a building or the fire compartment. In that case, the heat content per unit area is called the fire load density. The higher its value, the greater the potential fire severity and damage as the duration of the burning period of the fire is considered proportional to fire load.

Based on Pettersson (1976), fire load per unit area is given by the total internal surface area of the fire compartment and is calculated from the relationship:

$$q = \frac{\Sigma M_v \Delta h_c}{A_t} \qquad \text{MJ/m}^2 \text{ (total surface area)} \qquad [2.1.1]$$

where M_v is the total weight of each single combustible item in the fire compartment, (kg).

Δh_c is the effective calorific value of each combustible item, (MJ/kg).

A_t is total internal surface area of the fire compartment, (m^2).

Fire load density in buildings is most often expressed in units of MJ/m^2 (floor area). It must be noted that many European references such as Pettersson (1976) use MJ/m^2 of total bounding internal surfaces of the room, which can cause major errors if the distinction is not clear.

However, the total internal surface area and the floor area can be converted from one to the other by using

$$A_t = 2[A_f + H_t(L + W)] \qquad \text{m}^2 \qquad [2.1.2]$$

where A_t is the total internal surface area, (m^2).

A_f is the floor area, (m^2).

H_t is the height of the fire compartment, (m).

L is the length of the fire compartment, (m).

W is the width of the fire compartment, (m).

In estimating fire loads in fire compartments, the combustion properties of the fire load, such as their nature, weight, thickness, surface area and their location play a critical role. Therefore, fire loads are commonly divided into two categories:

a) fixed fire load that consists of exposed combustible materials permanently affixed to walls, ceilings or floors plus any other built in fixtures.

b) moveable fire load that consists of combustible furniture and other contents which are brought into the building for the use of the occupant.

In practice, the fire load will vary with the occupancy, with the location in the building and with time. However, it is possible to determine by means of statistical surveys the probability of the presence of a certain fire load density in various occupancies such as motels, hotels, offices, schools and hospitals.

2.2 Assumptions Made to Estimate the Fire Load

Although many of surveys have been conducted during the past, most of them have made similar assumptions (Narayanan, 1994) in order to simplify the fire load estimation.

These assumptions were:

a) Throughout the building, combustible materials are uniformly distributed.
b) All combustible material would be involved in the fire.
c) All combustible material in the firecell would undergo total combustion during the fire.

d) Fire load can be measured as the sum of the heat contents of the different materials (ie cellulosics and non-cellulosics) but will be given in a more conventional way by being directly evaluated on a wood equivalent basis. Thus, the total fire load will be expressed in mass of wood equivalent.

2.3 Survey Procedures

According to Narayanan (1994), after defining and selecting the type of building occupancy needed for the survey, the fire load survey was carried out by first classifying combustibles into fixed and moveable fire loads, preferably into a number of types and sizes so that little weighing or none at all is needed to obtain weight estimates in the future. The next step involved the actual weighing of each moveable combustible item in the compartment, and total sampling of all the floor area.

Besides weighing each item in the fire compartment, during his fire load survey, Mabin (1994) also estimated the number of different materials used by weight, ie. the percentage of wood, metal and plastic items. This is a reasonable method as in this way, the weight of each material used in an object can be approximated.

For example:

A chair weighs 12 kg

Estimate: 60% of the weight is steel
30% of the weight is wood
10% of the weight is foam (Mabin, 1994)

For combustible items, especially fixed in place combustibles that could not be easily weighed, their dimensions were measured, volumes calculated and multiplied by specific density to estimate the equivalent weight of the combustible materials. These were then used to derive the total calorific value in MJ of the combustibles within the building. Finally, the fire loads were divided by the floor area to obtain the fire load density (MJ/m^2).

2.4 Survey Results

In order to determine the magnitude of fire load, many countries have conducted statistical investigations on residential buildings, office buildings, schools, hospitals, hostels and so on. Note that in order to ease the comparisons between the results from each survey, all the results, which are given in units kg/m^3, will be multiplied by a net calorific value of 16.7 MJ/kg (which is a number assumed for wood materials throughout this report). These extra calculations can be found in Table 2.4.1, 2.4.2, 2.4.5, 2.4.6, 2.4.7, 2.4.8, and 2.4.12.

Although fire load surveys have been conducted since 1891 (Heaney, 1971), due to the awareness of the need to measure fire load in structure by the National Bureau of Standards (NBS), the National Academy of Sciences and the General Services Administration (GSA) (America Burning, 1973), it has been generally recognized that more data is still required.

During the period 1928 to 1940, NBS has conducted surveys of fire loads in residences, offices, schools, hospitals and a few mercantile buildings (Sup. Doc., 1942). In 1947, an enlarged survey was made of the combustible contents of mercantile and manufacturing buildings (Ingberg et al., 1957). Results of these surveys are summarized in Table 2.4.1.

Type of Occupancy		Combustible Contents						
		Number Surveyed	Floor Area (m^2)	Average (kg/m^2)	Range of Maximum Values for Single Occupied room (kg/m^2)	Range of Maximum Values for Single Occupied room (MJ/m^2)	Maximum for Any Area (kg/m2)	Maximum for Any Area (MJ/m^2)
Residence		13	760	44	40 to 69	668 to 1152	242 (linen closet)	4041 (linen closet)
Hospital		1	13400	14	15 to 110	251 to 1837	94 (service store) 113 (laundry, clothes storage)	1570 (service store) 1890 (laundry, clothes storage)
School		6	6725	75	35 to 193	585 to 3223	1124 (textbook storeroom)	18770 (textbook storeroom)
Mercantile (department store)		2	103000	51	-	-	232 (paint department)	3875 (paint department)
Manufacturing	Furniture Factory	2	51075	76				
	Mattress Factory	2	14473	81	-	-	577 (veneer storage)	9636 (veneer storage)
	Clothing Factory	2	8519	53			513 (paint shop) 824 (paper storage)	8567 (paint shop) 13760 (paper storage)
	Printing Plant	2	17814	168				
Warehouse	General	4	48140	124	-	-	1263	21092
	Printing	1	12550	860				
Office		82	8280	91	35 to 212	585 to 3540	424 (heavy files)	7081 (heavy files)

Table 2.4.1: Weights of combustible contents (based on survey data reported by Robertson and Gross, 1970).

New fire load surveys have been conducted in various countries and occupancies by Nilsson (1970), Bonetti et al. (1975), CECM (1974), Baldwin et al. (1970), Berggren and Erikson (1970), Witteveen (1966), Forsberg and Thor (1971), and Magnusson and Pettersson (1972) due to the recognition that types of furnishings, interior finish and occupancy trends have changed over the last few decades. Many of these surveys have been summarized by Babrauskas (1976), shown in Table 2.4.2.

Cumulative Probability Percent	FIRE LOAD (in kg wood equivalent/ m2 floor area)									
	OFFICES									
	U.S.A. (Culver, 1976)		W. Germany (CECM, 1974)		Sweden (Berggren & Erikson, 1976)		Holland (Witteveen, 1966)		England (Baldwin et al., 1970)	
	(kg/m²)	(MJ/m²)	(kg/m²)	(MJ/m²)	(kg/m²)	(MJ/m²)	(kg/m²)	(MJ/m²)	(kg/m²)	(MJ/m²)
25	20	334	25	418	24	401	5	84	5	84
50	35	585	43	718	28	468	10	167	20	334
80	50	835	60	1002	38	635	24	401	32	535
99	100	1670	130	2171	70	1169	46	768	110	1837
	RESIDENCES						OTHERS (SWEDEN)			
	Sweden (Nilsson, 1970)				Schools (Forsberg & Thor, 1971)		Hotels (Forsberg & Thor, 1971)		Hospitals (Magnusson & Pettersson, 1970)	
	(kg/m²)	(MJ/m²)			(kg/m²)	(MJ/m²)	(kg/m²)	(MJ/m²)	(kg/m²)	(MJ/m²)
25	37	618			17	284	15	251	30	501
50	40	668			22	367	18	301	33	551
80	45	752			26	434	22	367	35	585
99	53	885			43	718	34	568	71	1186

Table 2.4.2: Cumulative frequency (probability) of fire loads (from Babrauskas 1976).

For the offices in Japan, it was found that the average fire load density is 62 kg/m^2 with a standard deviation of 10.2 kg/m^2 (Kawagoe and Sekine, 1964). For the offices in the Netherlands, the average fire load density is about 15 kg/m^2 (Rombouts et al., 1960,1961,1963) whereas in Washington, the average fire load for the offices is 52 kg/m^2 and the standard deviation is 17 kg/m^2 (Report B. M. S. 92, 1942).

In U.S. cities, the fuel load estimation is developed and presented for three primary urban land use classes: residential, commercial/service, and industrial, where the latter two classes are categorized as non-residential. Residential building fuel loads vary regionally from 123 to 150 kg/m^2, whereas for non-residential building classes, fuel loads vary from 39 to 273 kg/m^2. These results indicate that average U.S. urban area fuel loads range from 14 to 21 kg/m^2 (Bush, Anno, McCoy, Gaj and Small, 1991).

Due to the extreme fire risk in Chinese restaurants in Hong Kong, Chow (1994) has carried out surveys on the fire load in fifteen Chinese "Yam Cha" restaurants of different sizes. It is found out that fire load in the Chinese restaurants is quite high as large amounts of combustible materials such as furniture, partitions, carpets and tablecloths are stored, and most furnishing materials used in dining halls always consist of synthetic materials. Total fire load density in restaurants, excluding toilets and storage, varied from 75 MJ/m^2 to 867 MJ/m^2; in the dining hall itself it varied from 69 MJ/m^2 to 1055 MJ/m^2 whereas in the kitchen, the total fire load density varied from 111 MJ/m^2 to 303 MJ/m^2. The mean fire load density of Chinese restaurants in Hong Kong is 284 MJ/m^2 in the entire restaurant, 312 MJ/m^2 in the dining hall and 216 MJ/m^2 in the kitchen.

Table 2.4.3 presents the summary of the fire load survey in the fifteen Chinese restaurants whereas Table 2.4.4 shows the summarized fire load in restaurant number 6 (Chow 1994).

ENTIRE RESTAURANT						
				Total Fire Load Density		
Restaurant No.	Total Floor Area, A_f (m^2)	Total Fire Load (MJ) (x 10^3)	Moveable Fire Load to Total Fire Load (%)	(MJ/m^2)	Equivalent Weight of Wood (kg/m^2)	Equivalent Period, t_e (min)
1	120	104	40.3	867	46	148
2	193	29.9	41.4	156	9	39
3	276	70.6	86.2	256	14	80
4	462	38.3	54.3	83	5	42
5	476	78.9	31.2	166	9	85
6	575	134	51.8	234	13	131
7	800	59.8	57.5	75	4	57
8	1020	152	43.3	149	8	133
9	1076	519	87.6	482	26	410
10	1166	254	21.2	217	12	204
11	1300	824	41.1	634	34	684
12	1360	286	35.5	210	12	235
13	1367	290	50.8	212	12	236
14	1586	404	42.7	255	14	301
15	2541	653	32.8	257	14	460

DINING HALL								
						Total Fire Load Density		
Restaurant No.	Length, L (m)	Width, W (m)	Total Floor Area, A_f (m^2)	Total Fire Load (MJ) (x 10^3)	Moveable Fire Load (%)	(MJ/m^2)	Equivalent Weight of Wood (kg/m^2)	Equivalent Period, t_e (min)
1	11.6	7.76	90	94.9	37.7	1055	60	170
2	16.2	10.68	173	25.5	31.8	148	8	39
3	20.14	10.08	203	61.7	84.6	304	17	89
4	24	18	432	33	48.1	77	5	40
5	25.87	17.24	446	74.1	27.3	167	9	89
6	25	20	500	120	46.3	240	13	141
7	30	25	750	51.6	51.2	69	4	55
8	37.35	25	930	116	27.2	125	7	116
9	30.2	25.17	760	469	86.4	617	33	498
10	38.86	23.31	906	221	17.1	244	13	221
11	40	30	1200	774	37.6	645	35	730
12	36.29	35	1270	269	31.9	212	12	252
13	50	25.74	1287	273	48.2	212	12	243
14	44.16	26.49	1170	358	35.5	306	17	336
15	70.03	35	2451	632	31.1	258	14	487

KITCHEN								
						Total Fire Load Density		
Restaurant No.	Length, L (m)	Width, W (m)	Total Floor Area, A_f (m^2)	Total Fire Load (MJ) (x 10^3)	Moveable Fire Load (%)	(MJ/m^2)	Equivalent Weight of Wood (kg/m^2)	Equivalent Period, t_e (min)
1	7.5	4	30	9.07	67.4	303	16	51
2	5.5	3.6	20	4.4	97.3	220	12	25
3	12.08	6.04	73	8.93	97.7	123	7	50
4	6	5	30	5.38	92.5	180	10	30
5	6	5	30	4.81	91.6	161	9	27
6	15	5	75	14.4	98.0	192	11	80
7	10	5	50	8.26	96.9	166	9	46
8	11.61	7.75	90	35.9	95.3	400	22	201
9	35.55	8.89	316	49.4	99.0	157	9	276
10	22.8	11.4	260	32.6	96.0	126	7	182
11	12.25	8.16	100	50.1	94.9	501	27	280
12	15	6	90	16.6	93.5	185	10	93
13	10.33	7.75	80	16.5	94.2	206	11	92
14	23.55	17.66	416	45.9	98.5	111	6	256
15	13.42	6.71	90	20.1	86.4	224	12	112

Table 2.4.3: Summary of the fire load survey in fifteen Chinese restaurants (from Chow, 1994).

Location	Floor Area (m^2)	Type	Items	Materials	Mass (kg)	Calorific Value (MJ/kg)	Heat Potential (MJ)
Dining Hall	500	Moveable	Table Chair	Wood*	2085	19	39615
		Moveable	Cloth/curtains	Textile	380	17	6460
		Moveable	Partition	Wood	400	19	7600
		Moveable	Container	Plastics	26	22	572
		Moveable	Baskets	Plastics	52	22	1144
		Fixed	Ceiling	Wood	1900	19	36100
		Fixed	Wallpaper	Paper	500	16	8000
		Fixed	Paints	Polymer	50	26	1300
		Fixed	Electrical	PVC	50	22	1100
		Fixed	Carpet	Wool	760	21	15960
Kitchen	75	Moveable	Bench	Wood	100	19	1900
		Moveable	Cupboard	Wood	400	19	7600
		Moveable	Food	Alcohol	56	38	2128
		Moveable	Food	Rice Flour Sugar	140	15	2100
		Moveable	Food	Meat Bread	140	10	1400
		Moveable	Food	Oil	20	42	840
		Fixed	Paints	Paints	5	37	185
		Fixed	Electrical	PVC	5	22	110

Table 2.4.4: Survey on fire load in restaurant number 6 (from Chow, 1994).

The main purpose of the survey of fire loads in Hackney Hospital conducted by Green (1977) is to predict the fire severity, and hence required fire resistance, in order to prevent any severe risk to life should a fire occur. Green's (1977) fire load survey included seven upgraded and eighteen non-upgraded wards, storage rooms, the x-ray department, pathology block, administrative offices, occupational therapy department and psychiatric day centre.

Three parameters were calculated for each room or fire compartment, which were the required fire resistance, t_f, fire load density, α, and fire load per unit area of ventilation, γ. According to this survey, the fire load in wards, which were considered to be of primary concern to life during a fire, is well below that of offices. Therefore, this puts the wards in the "low fire" category. However, for other areas, such as the storage rooms, the fire loads range from moderate to high.

Table 2.4.5 to 2.4.8 show the summarized fire load survey conducted by Green (1977) in Hackney Hospital.

Sample	Fire resistance, t_f (min)	Fire Load Density, α		Fire Load per Unit Area of Ventilation, γ	
		(kg/m²)	(MJ/m²)	(kg/m²)	(MJ/m²)
Upgraded wards (excluding small rooms)					
Mean	15.4	8.4	140	55.4	925
Standard deviation	5.6	2.4	40.1	16.7	279
Upgraded wards (including small rooms)					
Mean	22	12	200	74.4	1242
Standard deviation	6.2	3.9	65.1	20.3	339
Non-upgraded wards					
Mean	16.8	10.8	181	50.4	842
Standard deviation	4.2	1.5	25.1	12.5	209
Large wards					
Mean	16.4	10.3	172	51.8	865
Standard deviation	4.5	2.2	36.7	13.6	227
Small wards					
Mean	13.4	12.3	206	69.4	1159
Standard deviation	5.2	2.6	43.4	35.4	592
All wards					
Mean	15.8	10.6	177	55.1	920
Standard deviation	4.7	2.4	40.1	20.3	340
95% values	24	14.8	247	90.4	1510

Table 2.4.5: Summary results for hospital wards (from Green, 1977).

Store	Fire resistance, t_f (min)	Fire Load Density, α		Fire Load per Unit Area of Ventilation, γ	
		(kg/m²)	(MJ/m²)	(kg/m²)	(MJ/m²)
General stores	66.6	46.4	775	192	3206
Stationery store	190	125	2088	711.6	11884
H block store	197	103	1720	690	11523
Pathology store (stationery)	411	327	5461	2574	42986
Psychiatric day (material store)	48	34.5	576	280	4676
Paints store	79	75	1253	429.8	7178
Medical records					
File store (3)	301.4	226.8	3788	1182.6	19750
File store (5)	521	358.3	5984	2045.5	34160
All stores					
Mean	226	162	2705	1013	16917
Standard deviation	172	126.5	2113	868	14500
95% values	573	416	6948	2758	46060

Table 2.4.6: Results for storage rooms in Hackney Hospital (from Green, 1977).

Department	Fire resistance, t_f (min)	Fire Load Density, α (kg/m^2)	(MJ/m^2)	Fire Load per Unit Area of Ventilation, γ (kg/m^2)	(MJ/m^2)
Antenatal					
Clinic	8	6.2	104	27	451
Waiting	6.5	4.6	76.8	19	317
Physiotherapy					
Gymnasium	6.4	3.7	61.8	22.7	379
Ward	9.9	6	100	35	585
Occupational therapy					
North	13.3	6.6	110	50.4	842
South	36.4	17	284	164	2739
Medical records					
Central office	121	115	1921	158	2639
Office 1	8	8	134	32	534
Office 2	74	81	1353	177	2956
Social worker's office	9.6	27	451	71	1186
Casualty	5.2	2.6	43.4	35.4	591
Rest room	9	6.5	109	27.5	459
Treatment	11.5	11	184	38.4	641
Waiting room	14	14.6	244	34.8	581
Psychiatric day					
Staff room	15	15.5	259	47.2	788
Group therapy (1)	23.8	16	267	107.1	1789
Group therapy (2)	13.8	11.9	199	53	885
Occupational therapy (quite room)	25.4	13.5	225	158.7	2650
Dining room	15.6	7.7	129	69.6	1162
Kitchen	19.6	13.2	220	92.6	1546
Store (O. T. Material)	48	34.5	576	280	4676
Occupational therapy office	86	48.3	807	518.5	8659
Occupational therapy beauty	14.6	10.2	170	68.2	1139
O. T. Carpentry	66.4	16.7	279	387.6	6473
O. T. Painting	26.6	12.5	209	156.8	2619
O. T. Packing	27.5	25.5	426	541	9035
Male changing	35.1	55	928	108	1804
Interview (1)	11.7	12.1	202	34.5	576
Interview (2)	11.8	14.4	240	42.8	715
Summary for psychiatric day unit					
Mean	35.9	21.6	361	199	3323
Standard deviation	25.4	15.1	252	176	2940
X-ray					
Film file	1575	691.8	11553	1466.7	24494
Reception	23.7	11.4	191	152	2538
Pathology					
Laboratory (1)	57	36	601	274.9	4591
Laboratory (2)	37	21.4	357	156	2605
Reception	14	8.8	147	58.2	972
Storeroom	411	327	5461	2574	42986

Table 2.4.7: Results for miscellaneous rooms and departments in Hackney Hospital (from Green, 1977).

Ward	Fire resistance, t_f (min)	Fire Load Density, α (kg/m^2)	(MJ/m^2)	Fire Load per Unit Area of Ventilation, γ (kg/m^2)	(MJ/m^2)
One-bed ward	11	12.6	210	49.6	828
Four-bed ward	19	16.2	271	68	1136
Twenty-bed ward	25	16.6	277	77	1286

Table 2.4.8: Summary of results for three theoretical wards (from Green, 1977).

Besides fire load surveys conducted in Europe, U.S. and other countries, a small number of fire load surveys have also been carried out in New Zealand by Barnett (1984), Narayanan (1994) and Mabin (1994). The main objective of carrying out fire load surveys in New Zealand was to enable a comparison to be made with fire load values used in Europe and other countries. This is due to increased awareness of great variation in fire load used between various regions of the world due to different cultures, climatic conditions and the nature of construction materials.

Barnett's (1984) fire load surveys were conducted for one sample from each of the following occupancies:

Building Type	**Description**
Hospital	Ward block
Hostel	Student
Office	Insurance
Shop	House furnishings
Factory	Stationery manufacture

Table 2.4.9: Building occupancies surveyed by Barnett (1984).

Table 2.4.10 shows the summarized results of floor areas and total fire loads, whereas Table 2.4.11 shows the summarized results of the unit fire load density values (Barnett, 1984).

Building Type	Area (m^2)	Total Surveyed Fire Load (kg) (x 10^3)
Hospital	503	27
Hostel	387	9
Office	1217	27
Shop	2284	64
Factory	3697	1161

Table 2.4.10: Summarized results of floor areas and total fire loads (from Barnett, 1984).

Building Type	SURVEY			
	Fixed	Moveable	Total	
	MJ/m^2	MJ/m^2	MJ/m^2	kg/m^2
Hospital	810	228	1038	54
Hostel	188	263	451	23
Office	212	224	436	22
Shop	257	293	550	28
Factory	185	6091	6276	314

Table 2.4.11: Summarized results of the unit fire load density values (from Barnett, 1984).

From Table 2.4.11, the fire load densities were first calculated as energy density terms in MJ/m^2 and then converted to mass density terms in kg/m^2 as wood equivalents using the gross calorific value of wood as 20 MJ/kg. This calorific value might be too high as it relates to "oven dry" wood. A more correct value might be 15 MJ/kg related to wood as normally found in buildings. Therefore, Barnett (1984) suggested that in order to be fully consistent, when one weighs wood at normal moisture content in a fire load survey, it should be converted to a weight of "oven dry" wood equivalents by multiplying by $\frac{15}{20}$ or 0.75.

Table 2.4.12 shows the summary of pilot fire load survey results conducted by Barnett, 1984.

Building Type	Hospital	Hostel	Office	Shop	Factory
Area, A_f (m^2)	508	387	1217	2284	3697
Fire Loadings					
Total B (kg)	27000	9000	27000	64000	1161000
Unit b (kg/m^2)	54	23	22	28	314
b x 16.7MJ/kg (MJ/m^2)	902	384	367	468	5244
Ventilation Factors					
Total F_v (m$^{5/2}$)	246	98	552	520	91
Unit f_v (m$^{3/2}$)	0.49	0.25	0.45	0.23	0.025
Burn Rates					
Total R $^{(1)}$ (kg/s)	22.6	7.42	22.3	47.7	8.34
Unit r (kg/s.m^2)	0.045	0.019	0.018	0.021	0.002
Duration					
Time t_s (secs)	1204	1200	1200	1342	139163
Time t_m (mins)	20	20	20	22	2319
Time t_h (hours)	0.3	0.3	0.3	0.4	39

$^{(1)}$ $R = 0.092F_v$

Table 2.4.12: Summary of pilot fire load survey results (by Barnett, 1984).

Fire load surveys conducted by Narayanan (1994) included five life insurance offices in Wellington. The survey is conducted by dividing the fire load into fixed and moveable fire load. The survey figure of the fire loads in life insurance offices in Wellington City is shown in Table 2.4.13 and Table 2.4.14 shows the resulting statistical values for the fixed, moveable and total fire load results. Mabin's (1994) surveys involved weighing each item and estimating the respective constituents by weight for ten samples from each occupancy such as hotels, motels, civil offices and other offices.

	Office Sample									
Items	A1		A2		A3		A4		A5	
Floor Area (m^2)	477		1116		1205		425		776	
Fire Loads:	Total (MJ)	Ave. (MJ/m^2)	Total (MJ)	Ave. (MJ/m^2)	Total (MJ)	Ave. (MJ/m^2)	Total (MJ)	Ave. (MJ/m^2)	Total (MJ)	Ave. (MJ/m^2)
Fixed Load	63318	133	115029	103	132778	110	47477	112	244587	315
Moveable Load										
(a) Contents	74529	156	190523	171	586337	487	212870	501	168574	217
(b) Furniture	136379	268	169576	152	421615	350	75229	177	105806	137
Average Moveable		442		323		837		678		354
Total Fire Load	274226	575	475128	426	1141677	947	335576	790	519636	670

Table 2.4.13: Survey figures of fire loads in life insurance offices in Wellington city (by Narayanan, 1994).

Item	Statistical Value					
	Fixed Fire Load		Moveable Fire Load		Total	
	MJ/m^2	kg/m^2	MJ/m^2	kg/m^2	MJ/m^2	kg/m^2
Mean, X	164	9.12	476	26.5	681	37.9
Standard deviation, s	84	4.7	234	13.0	227	12.6
90% value (1.39X)					947	52.6
80% value (1.28X)	210	11.7	610	33.9	872	48.4
Coefficient of variation ([X/s] x 100)	51%		49%		33%	

Table 2.4.14: Results of the normal distribution of fire loads in New Zealand life insurance offices (by Narayanan, 1994).

In order to see the comparisons of results from all the previous fire load surveys, Table 2.4.15 shows the moveable fire load densities from different surveys.

	Office (MJ/m²)		Motels / Hotels (MJ/m²)	
Survey conducted by	Mean	Standard deviation	Mean	Standard deviation
Mabin (1994)	2110	1149	251	58
Barnett (1984)	224	-	263	-
Narayanan (1994)	476	233	-	-
F.E.D.G (1994)**	800	-	300	-
Pettersson (1976)**	600	-	270	-
B.S.F.S.E. (1993)	420	-	310	-
Swedish Data*	411	334	310^+	92^+
U.S. Data*	555	625	-	-
European Data*	420	370	310^+	104^+
Swiss Data*	750	-	-	-
Dutch Data*	410	330	-	-
French Data*	330	400	-	-

**CIB W14 (1983) ~ Table A1.3.4.*

$^+$CIB W14 (1983) ~ Table A1.3.3.

***Swiss Data.*

Table 2.4.15: Comparison of moveable fire load densities (from Mabin, 1994).

From Table 2.4.15 above, it can be seen that the mean values of the moveable fire load densities for offices range from 224 to 800 MJ/m^2, with the exception of the value given by Mabin (1994). Mabin's (1994) mean value for the fire load density in the offices, which is 2110 MJ/m^2, is over estimated and is not compatible with the ranges given by the other surveys. Therefore, this value is ignored. For motels/hotels, the fire load density is more or less the same with ranges from 251 to 310 MJ/m^2.

2.5 Conclusions

Besides taking into account ventilation characteristics, previous fire load surveys have measured only mass, calorific value and the fire load densities by dividing them by the floor area. There is a lack of data of fuel load, which also includes the exposed surface area of the fuel items.

However, some of the assumptions made and the survey procedures used in the past are used in the current survey. The previous survey data can also be used as a guide and comparison for the current survey.

Appendix A is extracted from CIB (1986). It gives average fire load densities using data from Switzerland.

3. PREDICTING THE BURNING CHARACTERISTICS AND HRR OF FUELS

As mentioned in Chapter 2, fire load surveys conducted previously are mainly determined by the total mass of combustible per unit floor area and the net calorific value, in order to predict the possible heat release rate. However, present investigations have confirmed the need to include the exposed surface area of the fire load in the surveys. This is because during the fire, the material surface area will gradually be reduced. The reduction in surface area leads to a stage where the burning rate is no longer ventilation controlled but fuel surface controlled. In other words, the mass loss rate of the fuel is no longer dependent on the ventilation characteristics but the surface area exposed to the fire.

This information about the exposed surface area of fuel is also needed for modelling fires using a program, such as COMPF (Babrauskas, 1979). Currently, research into modelling the post-flashover fires in a fire compartment is being carried out by a Ph.D. student, Yii (2000, in preparation) at the University of Canterbury, which has found that in order to produce a program which can accurately model post-flashover fires in fire compartments, the exposed surface area of the fuel load in a certain fire compartment must be known.

Besides that, the vast majority of the data from these previous surveys was based on wood fuel. When there were other types of fuel present in the same area, such as thermoplastic materials, their mass was converted into a calorifically equivalent mass of wood. This concept is obviously very crude, as it does not account for the specific fire behaviour of the combustible materials according to their nature, shape, size and other geometrical properties of the fuel.

Therefore, in order to refine the results of the upcoming fire load surveys on some of the selected building occupancies to investigate the effects of the surface areas on the value of the heat release rate, the fire load will be characterized into two major types: solid wood fuels and thermoplastic fuels.

Parameters needed in predicting the heat release rate such as density of the fuel, heat of combustion (net calorific value) and mass loss rate will be discussed in detail in the following paragraphs.

3.1 Solid Wood Fuel

3.1.1 Burning Behaviour

Wood is a highly diverse material and it takes sometimes to burn out completely. Many factors such as density, chemical composition, moisture content, permeability and char contraction factor have been identified as key variables that affect the burning behaviour of the wood. Typically, for wood materials, a sharp peak results from the burning of combustible pyrolyzate soon after ignition. As the wood chars, the heat release rate decreases because of the insulating effect of the char layer. If the wood is sufficiently thick, the heat release rate will stabilize to a steady state.

Figures 3.1.1.1 and 3.1.1.2 show the burning behaviour of wood materials in a real fire.

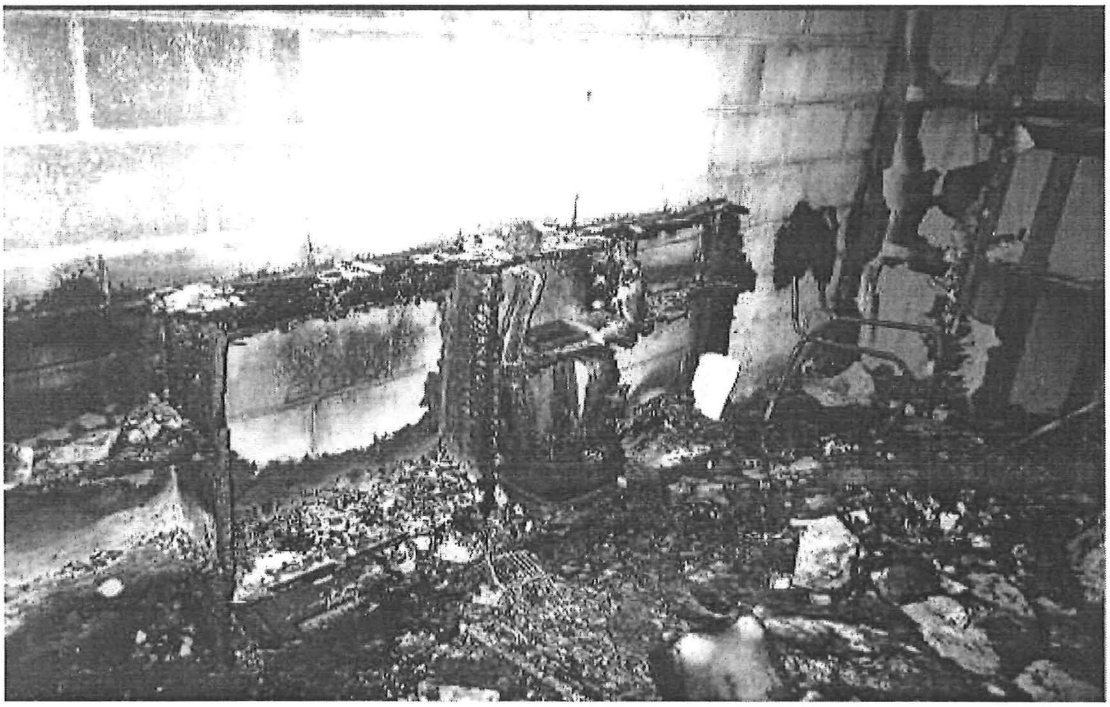


Figure 3.1.1.1: Burned materials inside a fire compartment.

From the figure above, it can be seen that the thinner parts, especially at the back of the bookshelf, have burned away, whereas the thicker parts still remain. The unexposed surface area of the books on the bookshelf is still in very good condition, with only a small proportion of the exposed surface burned and charred. Therefore, this illustrates that for thick wood materials such as books and papers which are bound together in bales, it took a long time to have a complete burnout. Besides that, due to the char layer having an insulating effect on the wood materials, the rate of burning will decrease, which in turn slows down the burnout process. Therefore, in a real fire, compared to the thermoplastic materials, it is still possible to see left over wood materials with their surface charred. This is because most of the time the fire dies down due to the lack of air to support the burning or the fire is put out by the fire service before the wood materials have a chance to go through complete burnout.

Figure 3.1.1.2: Partially burned wood sticks in crib.

The wood sticks in the crib shown in the figure above have only their exposed sides burned and charred. All the other surfaces, which are not exposed to the fire, are still in good condition, for wood sticks which are arranged in a crib as above have a much longer duration of burning if compared to a single burning wood stick. Besides that, the burning characteristics of a wood crib are completely different from a single wood stick with all its surfaces exposed. This is because for a wood crib, only parts of the areas are exposed to the fire with the other parts hidden from the exposure. Besides that, the radiation in the spaces between the wood sticks in the crib also affects the burning characteristic of the crib.

Combustible materials, such as files and papers, stored inside metal furniture, only fractionally involved in fire and most of them are left in very good condition. Ingberg's (1928) experiments and observations after real fires showed similar results. Figure 3.1.1.3 below shows the condition of the contents inside a filing cabinet after a real fire.

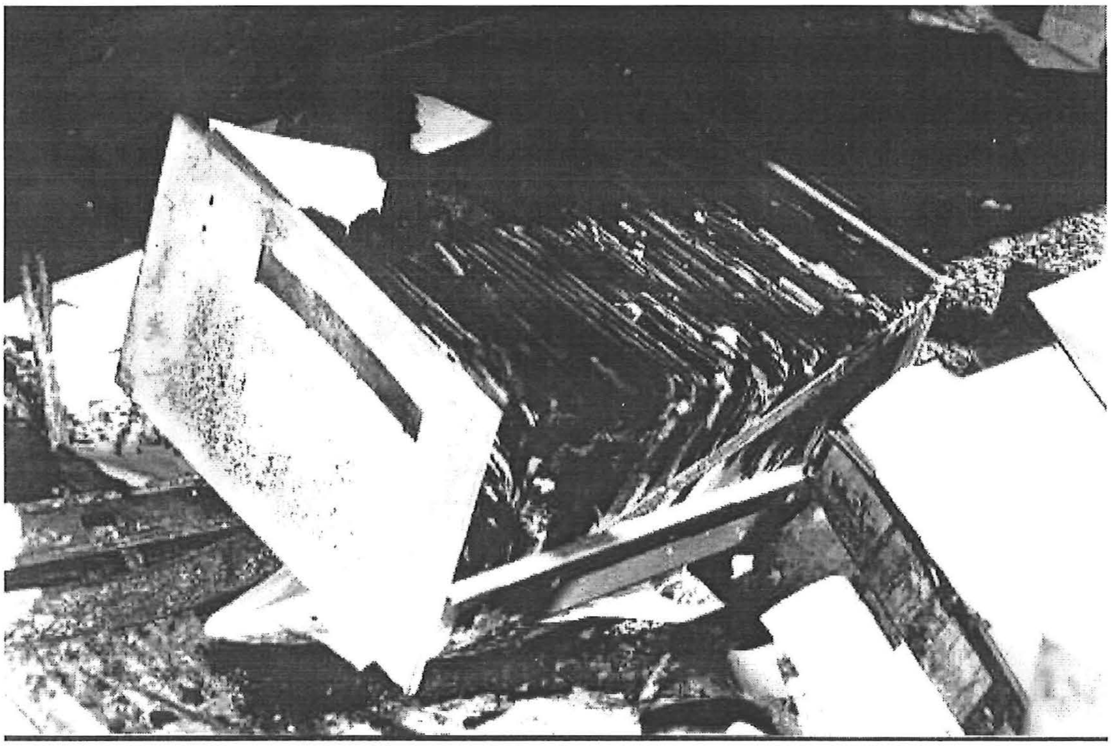


Figure 3.1.1.3: Condition of the filing cabinet content after a fire.

Although the burning behaviour of the wood materials is affected by the factors mentioned above, these effects, such as char insulation, are not taken into account in the current survey and modelling. For the current survey and modelling, it is assumed that all the wood materials ignited during the post-flashover fire continue to burn until all the materials have gone without any intervention.

3.1.2 Bulk Density

Wood varies significantly between species. Therefore, each species of wood has a different value of density. Density itself does not have a significant effect on heat release rate.

More generally, the effect of density is related to the chemical composition of the wood. It depends on the lignin content in the wood, as woods with higher lignin content would release less heat than those with less lignin under the same heating conditions.

For the above reason, it is very important to estimate a suitable value of density when calculating the heat release rate for the fire loads in the upcoming chapters. Therefore, to be consistent, a dry density of wood of 450 kg/m^3 is chosen for this report.

Besides requiring the bulk density of the wood to estimate the heat release rate, it is also important to estimate the mass of the fire load. This is especially important for fuel, which is too big or heavy to measure its mass, and only its volume can be measured.

3.1.3 Regression Rate

For wood, the burning rate depends on the thickness of the slab or the size of the sticks. Based on Babrauskas (1976), the surface regression rate for thick slabs is approximately constant at

$$v_p = 8.5 - 10.0 \times 10^{-6} \qquad \text{m/s} \qquad [3.1.3.1]$$

However, the burning rate for thinner slabs is faster, and thus the regression rate will increase according to

$$v_p = 2.2 - 10.0 \times 10^{-6} D^{-0.6} \qquad \text{m/s} \qquad [3.1.3.2]$$

where D is the thickness of the slab, (m).

Therefore, for wood materials, it is extremely important to know the regression rate, as the heat release rate is indirectly dependent on it. By changing the value of the regression rate, the heat release rate will change.

In order to have a constant and systematic result throughout this report for the wood type fire loads, a constant regression rate of 40 mm/hr (0.667 mm/min) (from Buchanan, 1994) on the surface has been assumed. It is important to note that this value can be changed according to the conditions present.

3.1.4 Mass Loss Rate Per Unit Area

Burning rate depends on the fuel properties, its configuration or orientation and the area involved which is controlled by the ignition and flame spread. Therefore, burning rate over that involved area may not be either steady or uniform. However, to eliminate the problem, the characteristic of uniformity can be expressed by the quantity in the form of mass loss rate per unit area. This describes how each point will burn.

A general predictive formula for mass loss rate per unit area is given by

$$\dot{m}'' = \frac{q_i}{L_v} \qquad \text{kg/s.m}^2 \qquad [3.1.4.1]$$

where q_i is the net heat flux, (kW/m^2).
L_v is the heat of gasification, (kJ/kg).

The net heat flux used in the Fire Simulator module of the FPEtool program (Deal, 1993) varies from 60 to 80 kW/m^2 which corresponds to a radiating surface (with an emissivity of 0.8) in the post-flashover fire.

The heat of gasification is the amount of energy required to pyrolize a unit mass of fuel. Drysdale (1998) reports heat of gasification values for wood ranging from 1.7 to 5.9 MJ/kg. The highest figure in the ranges should be used in order to get a realistic result.

In order to obtain the value of the mass loss rate per unit area, which is in agreement with the value obtained when the regression rate of 40 mm/hr as proposed in Section 3.1.3 above is used, the lowest figure of the net heat flux and the highest figure of the heat of gasification must be used.

Equation [3.1.4.1] is based on the assumption that the rate of heat release is proportional to the imposed heat flux with no influence of the thickness or shape of the fuel. However, as mentioned earlier in Section 3.1.3, the burning rate for wood materials is highly dependent on the thickness of the slab or the size of the sticks. Therefore, this equation cannot be used, as it does not include the surface regression rate. Details on how the mass loss rate per unit area is calculated for wood materials are discussed in Chapter 4.

3.1.5 Mass Loss Rate

a) Fuel Controlled:

Mass loss rate is defined as the mass of fuel consumed per unit time. During flashover, the mass loss rate will increase due to the ignition of all the combustible materials. The mass loss rate will become constant after flashover until a certain part of the material has been burned away. Then, it will decrease in proportion to the surface area left.

b) Ventilation Controlled:

In the past, based on Kawagoe and Sekine (1964), mass loss rate for wood materials is obtained by using the formula

$$R = 5.5 \sqrt{H}\ A_B \qquad \text{kg/min} \qquad [3.1.5.1]$$

or

$$R = 330 \sqrt{H}\ A_B \qquad \text{kg/min} \qquad [3.1.5.2]$$

where H is the height of the window, (m).

A_B is the area of the window, (m^2).

On the other hand, Thomas (1961) has been expressing the mass loss rate according to the following formula

$$R = 6\sqrt{H}\ A_B \qquad \text{kg/min} \qquad [3.1.5.3]$$

By looking equations [3.1.5.1], [3.1.5.2] and [3.1.5.3], in any case, the mass loss rate is proportional to the product of $\sqrt{H}$ and A_B.

However, present studies show that these assumptions for deriving the mass loss rate are not satisfactory. By calculating the mass loss rate of wood materials in proportion to the product of $\sqrt{H}$ and A_B, it is found that this method is a rather gross approximation, and even under closely controlled experimental conditions, the value of the mass loss rate could vary by ±10%.

Therefore, in order to have a more accurate prediction of the value of the mass loss rate, it is better to relate the mass loss rate to the exposed surface area of the materials. This is supported by the statement made earlier where during the flashover period, the mass loss rate will decrease in proportion to the surface area left.

It is important to know the value of the mass loss rate in order to calculate the heat release rate present as they are closely related.

3.1.6 Heat of Combustion

Heat of combustion, also known as the calorific value, is the amount of energy released during complete burning of the unit mass of fuel. Heat of combustion is required to calculate the value of the heat release rate.

The net calorific value, ΔH_c for some materials, especially wood, which contain some moisture under the ambient conditions, can be calculated by

$$\Delta H_c = \Delta H_{c,d}\,(1 - 0.001m_c) - 0.025\ m_c \qquad \text{MJ/kg} \qquad [3.1.6.1]$$

where $\Delta H_{c,d}$ is the heat of combustion of oven dry wood, (MJ/kg).

m_c is the moisture content as a percentage by weight given by

$m_c = (100 \times m_d) / (100 + m_d)$

where m_d is the moisture content as a percentage of the dry weight as usually used for wood products (Buchanan, 1998).

The typical range of net calorific value is found to be 17 to 20 MJ/kg (Barnett, 1984).

The use of the predicted mass loss rate as a function of time (see Section 3.1.5) to calculate the heat release rate depends upon the assumption of a constant calorific value. However, the calorific value of wood varies throughout the pyrolysis period as the carbon fraction going into char formation changes. Wood degrades by first pyrolyzing, then later charring. During the early pyrolyzing period, when mostly flaming combustion occurs, the net calorific value is in the range of 17 to 20 MJ/kg (Barnett, 1984). After flaming ceases, char oxidation becomes the more dominant mode, and the calorific value would rise to that of carbon, which is approximately in the range of 34 to 35 MJ/kg (Barnett, 1984).

However, as the heat release rate depends upon the constant value of the calorific value, the net calorific value during the flaming period, which is the main interest in fire growth, will be focussed on. This value can be especially useful since it can be used to calculate crudely the heat release rate when only the mass loss rate of the burning wood materials is known. It is assumed that the net calorific value of wood is constant throughout the flaming period.

3.2 Thermoplastic Fuel

3.2.1 Burning Behaviour

Thermoplastic fuels tend to melt and burn pool-like on the floor of a compartment. The upholstered furniture that is of most concern during the survey of the fire load will be upholstered chairs or sofas and mattresses. Mattresses and upholstered chairs are soft goods, which are constructed in a somewhat similar way: both use polyurethane foam and are covered with upholstery fabrics.

However, mattress fires are very different from upholstered chair fires. This is because mattresses are flat, whereas upholstered chairs normally have seats, backs and side arms. Besides that, an upholstered chair is normally constructed on a wood frame, whereas a mattress has no structural components, or else has steel innersprings. With mattresses which have no structural components and consist of a simple block of polyurethane foam, after the peak, all the solid polyurethane foam will melt and become a liquid-like pool on the floor. However, the quantity of the polyurethane foam will be less for mattresses that have a lot of air and steel springs. Therefore, besides having a smaller amount of pool on the floor from the melting of the foam, there will also be innerspring steel left after the peak for this type of mattress fire. There is no radiative heat transfer between the horizontal surface and the surroundings as with upholstered chair.

During the burning of upholstered chairs or sofas, which are usually made of polyurethane fabrics and foam, the fabrics usually shrink, melt and peel over almost this entire surface before continuing to burn. Then, the foam underneath the fabric bursts into flames and burns pool-like on the floor. For chairs or sofas, which are made of cotton fabrics, instead of shrinking and peeling, the fabrics will char and then burst into flames. Chairs that are made of wool fabrics will undergo charring and shrinking before busting into flame.

Figures 3.2.1.1 (a), (b) (c), and (d) below show the sequence of a burning chair, conducted in the fire lab of the University of Canterbury. They show the burning behaviour of an upholstered chair, with upholstered fabrics and foam constructed on the wood frame.

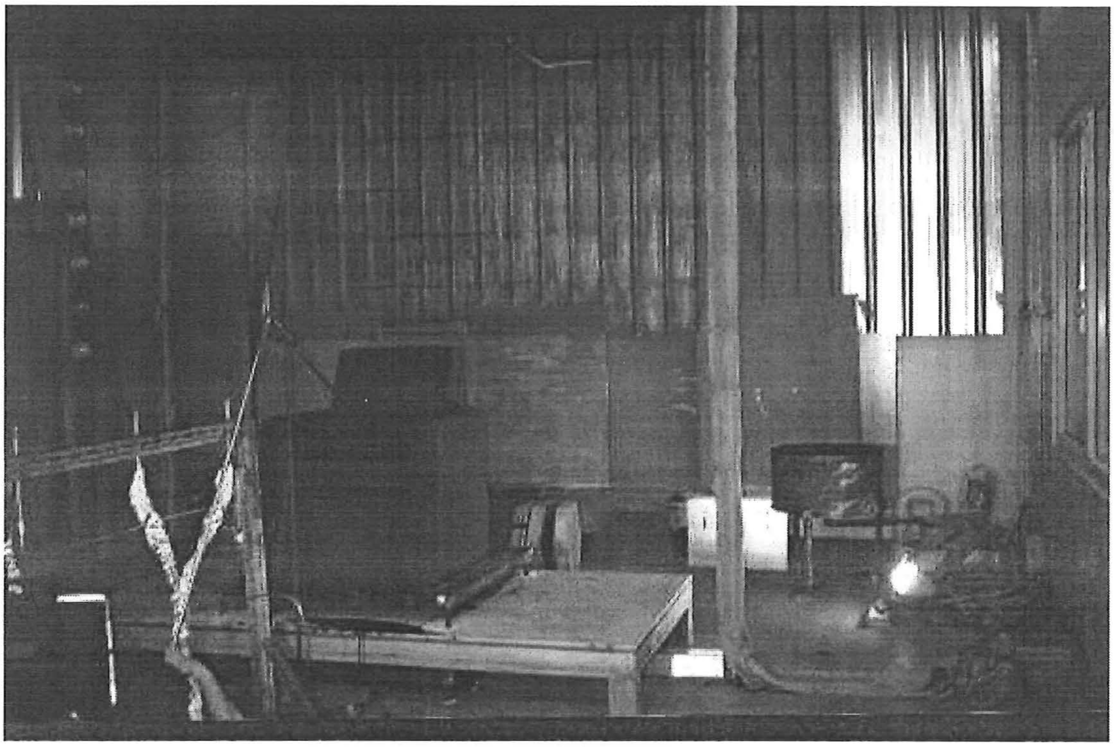


Figure 3.2.1.1(a): Layout of an upholstered chair on the furniture calorimeter in the fire lab.

The chair is made of polyurethane fabric and foam, and is constructed on a wood frame. The total mass of the chair is 18 kg, with approximately 24 % of the total mass consisting of upholstered materials. The dimension of the chair is 0.76 x 0.58 m.

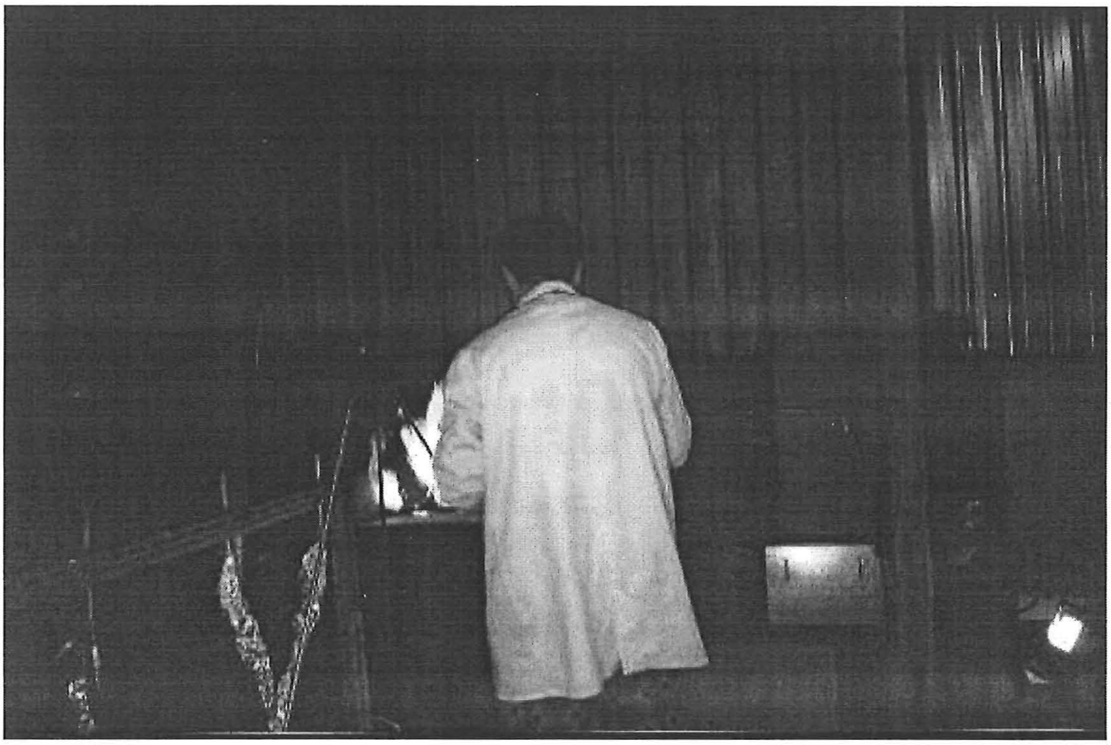


Figure 3.2.1.1(b): Ignition of the chair by a fire engineering student.

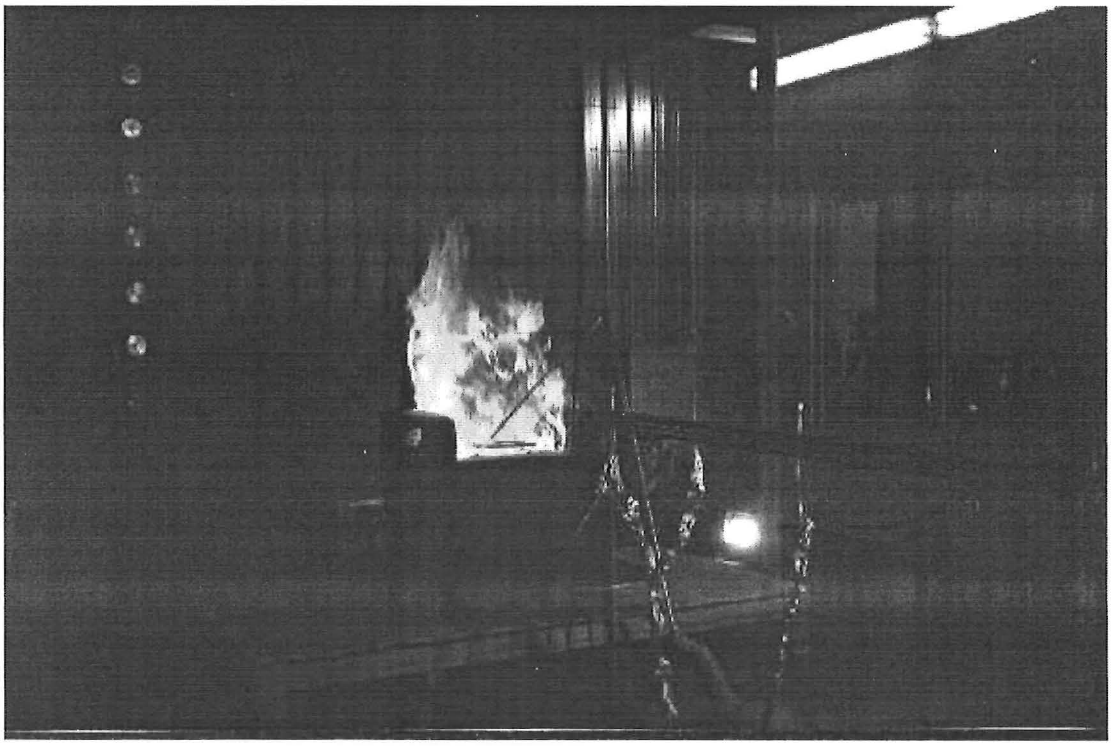


Figure 3.2.1.1(c): Liquidification of the chair about 3 minutes after the first ignition.

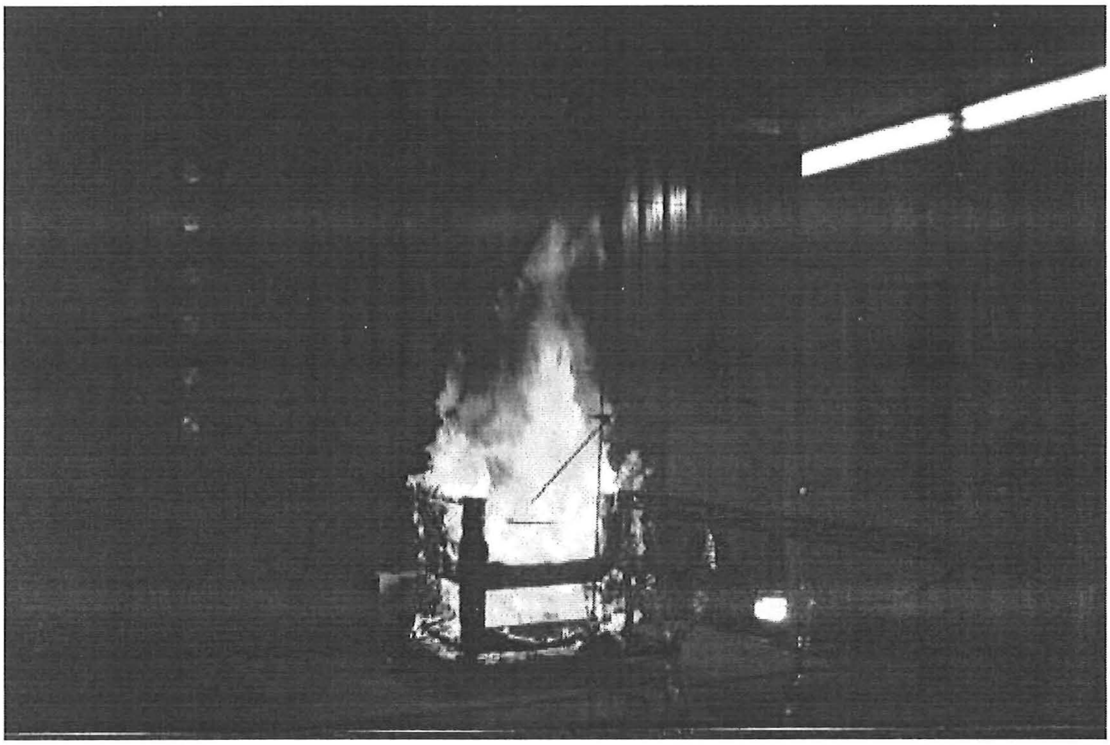


Figure 3.2.1.1(d): Peak burning of the chair approximately 6 minutes after the first ignition.

The seat of the chair is ignited by placing a gas burner above the surface, in the furniture calorimeter. When the surface and the foam underneath become sufficiently heated, a flame starts to spread outwards from the region first ignited. The situation is relatively complicated because there is radiative heat transfer between the horizontal surface and the surroundings. During the area growth process, the irradiance which the specimen sees changes dramatically. After a certain time, simple flame spread ceases to dominate and the chair starts to burn through; both sides begin to burn, pieces fall and burn, and a pool fires is created under the chair.

Table 3.2.1.1 below shows a system used by CBUF research group in defining different categories of the burning behaviour of upholstered furniture item (Sundström, 1996).

Category	Level of Safety provided	Burning Behaviour of Furniture Item	Control Value as Measured in the Cone Calorimeter
I	Should be safe in most room configurations.	Non-propagating fire.	65 kW/m^2
II	Should be safe in specified room configurations.	Peak HRR is limited.	CBUF furniture fire models.
III	Should be safe in specified room configurations for a certain time.	Time to a certain HRR is limited.	CBUF furniture fire models.

Table 3.2.1.1: A possible way of defining different categories of burning behaviour of upholstered furniture (from Sundström, 1996).

Besides defining the burning behaviour, Table 3.2.1.1 also shows the levels of safety that the furniture can be seen to represent, the corresponding burning behaviour and control values that can be measured in the cone calorimeter. Category I is independent of use, and the control values can be directly expressed in the cone calorimeter. However, upholstered furniture in categories II and III are not fully defined until the room configurations and the actual time periods are specified.

For this report, all the upholstered furniture is assumed to be burning as a propagating fire in the post-flashover conditions, so that once ignited, the fire propagates and progressively burns until the entire item is consumed.

3.2.2 Bulk Density:

Bulk density of upholstered furniture varies according to the materials. However, most upholstered furniture is made from polyurethane, therefore the density of the polyurethane will be used for most of the upholstered furniture. For other plastic materials such as blinds, rubbish bins and so on, a different plastic density will be used according to their material. The density of different thermoplastic materials can be found in the data provided in any plastic handbook. Table 3.2.2.1 below shows approximate densities of important plastics taken from Braun (1995).

Density (kg/m^3)	Material
800	Silicone rubber (silica filled up to 1.25)
830	Polymethylpentene
850-920	Polypropylene
890-930	High-pressure (low-density) polyethylene
910-920	Polybutene-1
910-930	Polyisobutylene
920-1000	Natural rubber
940-980	Low-pressure (high-density) polyethylene
1010-1040	Nylon 12
1030-1050	Nylon 11
1040-1060	Acrylonitrile-butadiene-styrene copolymers (ABS)
1040-1080	Polystyrene
1050-1070	Polyphenylene oxide
1060-1100	Styrene-acrylonitrile copolymers
1070-1090	Nylon 610
1120-1150	Nylon 6
1130-1160	Nylon 66
1100-1400	Epoxy resins, unsaturated polyester resins
1140-1170	Polyacrylonitrile
1150-1250	Cellulose acetobutyrate
1160-1200	Polymethyl methacrylate
1170-1200	Polyvinyl acetate
1180-1240	Cellulose propionate
1190-1350	Plasticized PVC (approx. 40% plasticizer)
1200-1220	Polycarbonate (based on bisphenol A)
1200-1260	Crosslinked polyurethanes
1260-1280	Phenol-formaldehyde resins (unfilled)
1210-1310	Polyvinyl alcohol
1250-1350	Cellulose acetate
1300-1410	Phenol-formaldehyde resins filled with organic materials (paper, fabric)
1300-1400	Polyvinyl fluoride
1340-1400	Celluloid
1380-1410	Polyethylene terephthalate
1380-1410	rigid PVC
1410-1430	Polyoxymethylene (polyformaldehyde)
1470-1520	Urea - and melamine-formaldehyde resins with organic fillers
1470-1550	Chlorinated PVC
1500-2000	Phenoplasts and aminoplasts with inorganic fillers
1700-1800	Polyvinylidene fluoride
1800-2300	Polyester and epoxy resins filled with glass fibers
1860-1880	Polyvinylidene chloride
2100-2200	Polytrifluoromonochloroethylene
2100-2300	Polytetrafluoroethylene

Table 3.2.2.1: Approximate densities of important plastics (from Braun, 1995).

For thermoplastic fuels, bulk density is extremely important in predicting the regression rate and the depth of the molten pool, which is indirectly needed to calculate the duration of burning and the heat release rate for a certain fuel item.

3.2.3 Mass Loss Rate Per Unit Area

In distinction to wood materials, the burning rate of thermoplastic materials does not depend on the surface regression rate. This is because the burning rate for thermoplastic materials depends much more strongly on surrounding gas and wall temperature than it does for wood materials. The burning rate for wood materials is largely self-controlled, and variations in external temperature and radiation do not produce marked changes in the rate of burning.

Therefore, the mass loss rate per unit area for thermoplastic materials from most of the references such as Quintiere (1998), and Babrauskas and Grayson (1992), depends on the net heat flux and the heat of gasification. Net heat flux is the incident radiation reaching the fuel surface (the total heat flux less any losses expressed as a heat flux through the fuel surface). Heat of gasification is the amount of energy required to pyrolyze a unit mass of fuel.

Based on the net heat flux and the heat of gasification, the mass loss rate per unit area for thermoplastic materials is given as Equation [3.1.4.1] in Section 3.1.4.

$$\dot{m}'' = \frac{q_i}{L_v} \qquad \text{kg/s.m}^2 \qquad [3.1.4.1]$$

where q_i is the net heat flux, (kW/m^2).

L_v is the heat of gasification, (kJ/kg).

However, to be consistent with the model proposed for the wood materials, which predicts the value of the heat release rate by using the regression rate instead of the net heat flux and the heat of gasification stated above, the value of the mass loss rate per unit area of the thermoplastic materials is simply taken from **Table 3-1.2** from SFPE (1995). The value chosen ranges from 0.018 to 0.034 kg/s.m^2. Table 3.2.3.1 below shows a simple version of **Table 3-1.2** from SFPE (1995).

Material	Density (kg/m^3)	ΔH_c (MJ/kg)	m" ($kg/s.m^2$)
Solid			
polymethylmethacrylate $(C_5H_8O_2)_n$	1184	24.9	0.02
polypropylene $(C_3H_6)_n$	905	43.2	0.018
polystyrene $(C_8H_8)_n$	1050	39.7	0.034

Table 3.2.3.1: Simple version of **Table 3-1.2** from SFPE (1995).

However, if one wish as to use the above equation [3.1.4.1] to calculate the mass loss rate per unit area instead of the value taken from Table 3.2.3.1, the net heat flux used can be taken as 60 to 80 kW/m^2 (Deal, 1993) in the post-flashover fire condition.

Drysdale (1998) reports heat of gasification values for plastics ranging from 1.2 to 3.7 MJ/kg. The highest figure in the ranges should be used in order to get a realistic result.

In order to obtain the value of the mass loss rate per unit area ranging from 0.018 to 0.034 as in Table 3.2.3.1 by using equation [3.1.4.1], the figure of the net heat flux must be at least 65 kW/m^2, and the highest figure of the heat of gasification must be used to get a realistic result.

3.2.4 Regression Rate

As mentioned in Section 3.2.3 above, the burning rate of thermoplastic materials does not depend on the surface regression rate, therefore there is no simple formula for the regression rate of the thermoplastic materials unlike the wood materials (as shown in Section 3.1.3).

However, to be consistent with the model proposed for the wood materials, it will be assumed that the pool burning of the thermoplastic materials will depend on the regression rate, as for wood materials, and not the net heat flux and the heat of gasification. Therefore, the value of the regression rate of the thermoplastic materials will be calculated by dividing the mass loss rate per unit area with the value of bulk density (more details discussed in Chapter 4).

3.2.5 Mass Loss Rate

As the thermoplastic materials tend to melt and burn in a pool-like manner during the burning period, pool fire theory is used to detail both. In order to predict the course of liquid pool fires, it is assumed that the material is pyrolyzed solely by the radiant heat flux from the compartment, which the material sees with a view factor of one.

Therefore, the mass loss rate is calculated by

$$R = \dot{m}''A_p \qquad \text{kg/s} \qquad [3.2.5.1]$$

where $\dot{m}''$ is the mass loss rate per unit area, (kg/s.m^2).
A_p is thermoplastic pool area, (m^2).

In order to be able to use the above equation to predict the mass loss rate, it is assumed that the materials are in a steady-state, well-stirred, post-flashover fire condition.

3.2.6 Heat of Combustion

As for wood materials, it is important to have the heat of combustion to calculate the value of the heat release rate.

Different types of thermoplastic materials have different values of net calorific values. It is again important to assume a constant value of net calorific value for the thermoplastic materials throughout the burning period to predict the heat release rate.

For most of the upholstered furniture, the net calorific value of polyurethane will be used, while for other plastic materials, the net calorific value will be chosen based on their materials. Data in Table 3.2.6.1 below shows the net calorific value for different plastic materials.

Material	MJ/kg
Plastics	
ABS	34-40
Acrylic	27-29
Celluloid	17-20
Epoxy	33-34
Melamine resin	16-19
Phenolformaldehyde	27-30
Polyester	30-31
Polyester, fiber reinforced	20-22
Polyrthylene	43-44
Polystyrene	39-40
Petroleum	40-42
Polyisocyanurate foam	22-26
Polycarbonate	28-30
Polypropylene	42-43
Polytetrafluoroethylene	5
Polyurethane	22-24
Polyurethane foam	23-28
Polyvinylchloride	16-17
Ureaformaldehyde	14-15
Ureaformaldehyde foam	12-15

Table 3.2.6.1: Net calorific value of plastic materials (from Barnett, 1984).

4. EFFECT OF FUEL SURFACE AREA ON HRR OF FUEL

The heat release rate generally increases with the increasing number of furniture items and the surface area exposed to the fire. Besides that, the type of fuel load and its arrangement also has a large impact on the outcome of the value of the heat release rate.

This chapter is divided into two categories: solid wood materials and thermoplastic materials.

4.1 Solid Wood Materials

4.1.1 Proposed Model to Calculate the HRR

In order to calculate the heat release rate of certain wood materials, a number of parameters are required such as density, regression rate, mass loss rate per unit area, mass loss rate and net calorific value of the material (refer to Chapter 3; Section 3.1).

Although wood materials vary significantly between species and have variable value of density (see Table 4.1.1.1), in order to be consistent throughout the presentation of this report, a dry density of wood of 450 kg/m^3 is assumed. In the same way, a constant regression rate of 40 mm/hr (0.667 mm/min) on the surface has been assumed (refer to Section 3.1.3). It is important to note that this value can be changed according to the conditions present in the future research.

Substance	Density, ρ (kg/m^3)
Wood (across the grain)	
Balsa 8.8 lb/ft^3	140
Cypress	460
Fir	420
Maple or oak	540
Yellow pine	640
White pine	430

Table 4.1.1.1: Densities for different species of wood (from **Table B-7**, SFPE, 1995)

By knowing the value of the bulk density and the regression rate, the mass loss rate per unit area of the fuel can be estimated by

$$\dot{m}'' = \rho \times v_p \qquad \text{kg/s.m}^2 \qquad [4.1.1.1]$$

where $\dot{m}''$ is the mass loss rate per unit area, (kg/s.m^2).

ρ is the value of the bulk density, (kg/m^3).

v_p is the regression rate, (m/s).

By knowing the exposed surface area of the combustible fuel load during the fire, the mass loss rate and the heat release rate of the exposed material can be calculated. In order to predict an accurate value of the surface area exposed, all the surface of the fuel load exposed to the fire must be taken into account. In time, the surface area exposed will be reduced according to the regression rate of the fuel. Besides that, the number of sides of the surface exposed to the fire is an important variable as well.

The equation proposed to calculate the area of the surface of a solid rectangular object exposed to fire is

$$A = (W_s - \beta\tau) \times (D_s - \beta\tau) \qquad \text{m}^2 \qquad [4.1.1.2]$$

where A is the surface area exposed to the fire, (m^2).

W_s is the width of the surface, (m).

D_s is the depth of the surface, (m).

β is a constant indicating how many sides of the width or depth of the surface are being regressed in the fire (ie. 1 or 2).

τ is the thickness of fuel burned with time, (m), given by $\tau = v_p \times t$.

where v_p is the regression rate, (m/s).

t is the time exposed, (s).

For example consider a solid block exposed to fire on six sides of its surface.

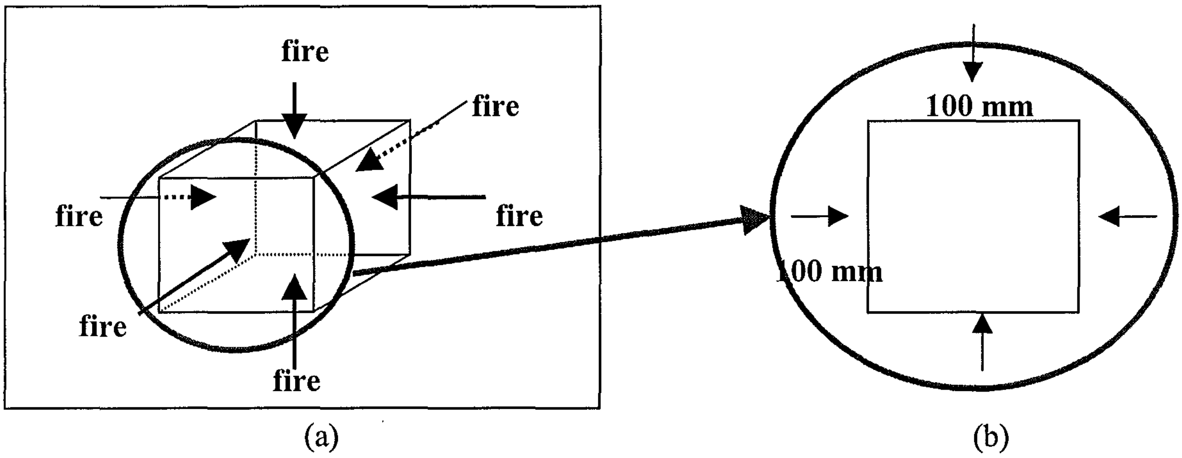


Figure 4.1.1.1: Typical block with its six surfaces exposed to fire.

Therefore by using equation [4.1.1.2], the surface area shown in Figure 4.1.1.1 (b) can be calculated with $W_s = D_s = 0.1$ m, $\beta = 2$ (burning from both sides), $v_p = 40$ mm/hr (1.11×10^{-5} m/s) and assume time of exposure, t = 5 s.

Thus,

$$A = [0.1 - (2 \times 1.11 \times 10^{-5} \times 5)] \times [0.1 - (2 \times 1.11 \times 10^{-5} \times 5)]$$
$$= 0.01 \text{ m}^2.$$

To get the overall surface area of the block exposed to the fire shown in Figure 4.1.1.1 (a), each surface must be calculated and added together, where for this case, the overall surface area exposed to the fire at 5 seconds of exposure is 6 x 0.01 = 0.06 m^2. If in any case the surface areas of a certain fuel are very difficult and complicated to estimate due to its irregular shape, then the shape of the fuel can be estimated as a simple shape, so that its surface areas exposed to the fire can be easily estimated. For example, a bookshelf full of books can be estimated as a solid block, instead of calculating for every single surface.

After knowing the value of the surface areas exposed, the mass loss rate can be calculated by

$$R = \dot{m}'' \times A \qquad \text{kg/s} \qquad [4.1.1.3]$$

where R is the mass loss rate, (kg/s).

$\dot{m}''$ is the mass loss rate per unit area, (kg/s.m^2).

A is the surface area exposed to the fire, (m^2).

The heat release rate then is simply determined as the product of mass loss rate and net calorific value, shown in equation [4.1.1.4] below. For this report, the net calorific value for wood used is assumed to be 16.7 MJ/kg (from Buchanan, 1994).

$$Q = R \times \Delta H_c \qquad \text{MW} \qquad [4.1.1.4]$$

where Q is the heat release rate, (MW).

R is the mass loss rate, (kg/s).

ΔH_c is the net calorific value, (MJ/kg).

Therefore, by knowing all the parameters mentioned above including the value of the exposed surface areas to the fire, the heat release rate of a certain burning fuel can be estimated. Therefore, it is really important to know the exact value of the surface area exposed in order to estimate an accurate value of heat release rate. It must be noted that this proposed model is for fuel burning during the post-flashover fire where it is assumed that all the fuel is ignited and all the surface areas are exposed to the fire at the same time.

Table 4.1.1.2 below shows the summary of how the heat release rate is calculated with the value of the exposed surface area known.

Density, ρ (kg/m^3)	Regression Rate, v_p (m/s)	Mass Loss Rate Per Unit Area, m'' (kg/s.m^2)	Surface Area, A (m^2)	Mass Loss Rate, R (kg/s)	Net Calorific Value, ΔH_c	HRR, Q (MW)
450	1.11×10^{-5}	$\rho \times v_p$	Equation [4.1.1.2]	m'' x A	16.7	$R \times \Delta H_c$

Table 4.1.1.2: Summary of the steps in calculating the heat release rate based on the surface areas exposed to fire for solid wood materials.

By knowing the amount of the available fuel inside a certain fire compartment, the duration of burning can also be calculated. This is because the duration of burning is directly proportional to the amount of the available fuel. In order to calculate the duration of burning, besides the value of the regression rate, the mass, thickness and the surface area of a certain fuel must also be known.

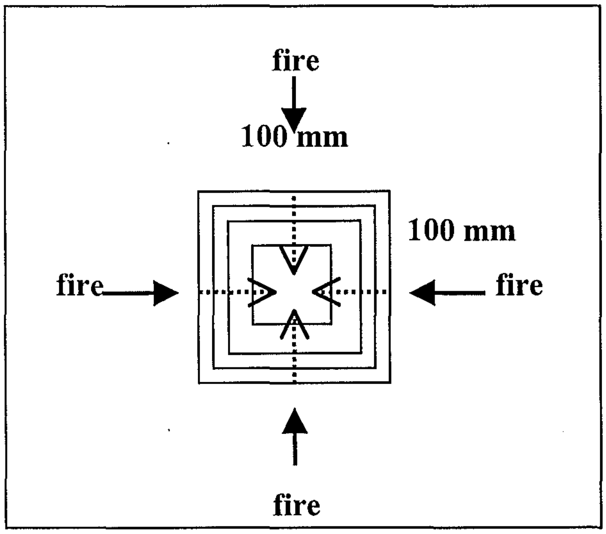
The equation below is used to calculate the duration of burning.

$$t_d = \frac{(D/\beta)}{v_p} \quad \text{s} \qquad [4.1.1.5]$$

where t_d is the duration of burning (s).
D is the thickness of the fuel (m).
v_p is the regression rate (m/s).
β is a constant indicating how many sides of the width or depth of the surface are being regressed in the fire (ie. 1 or 2).

It must be noted that the duration of burning calculated from equation [4.1.1.5] is the burning time of the fuel without any intervention, assuming all the combustible materials ignited at the same time (as during post-flashover fire).

For example, a typical wood stick with its thickness D = 100mm is exposed to fire from all four sides.



Therefore, the duration of burning is

$$t_d = \frac{(100/2)}{v_p}$$

In time, the stick will get thinner and thinner, shown in Figure 4.1.1.2.

Figure 4.1.1.2: Plan view of typical wood stick exposed to fire from all four sides.

Therefore, by using the proposed model mentioned above and with all the value of the parameters needed known, the heat release rate can be calculated. Following sections show how surface area can affect the output of the heat release rate.

4.1.2 Effects of Surface Area on HRR for Wood Sticks

For wood sticks with the following arrangement in 1 m^2 floor area (Figure 4.1.2.1), the heat release rate produced during the post-flashover fire is calculated based on the surface area of the sticks exposed, and the sticks thickness with a specific centre to centre spacing.

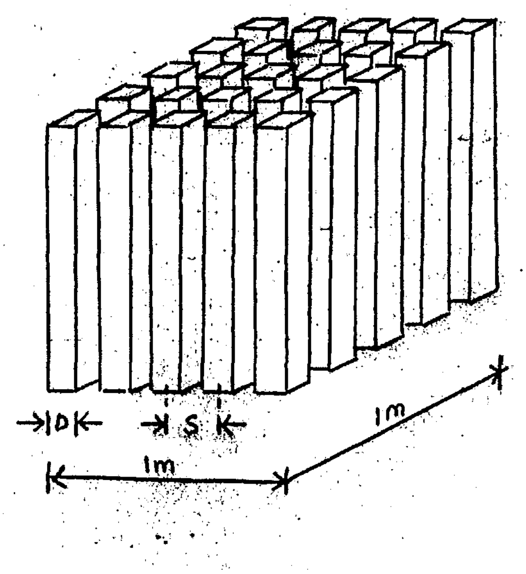


Figure 4.1.2.1: Typical sticks arrangement in 1 m^2 floor area.

The surface area of the sticks exposed is calculated by dividing a typical wood stick into a number of faces as shown in Figure 4.1.2.2. Then, by using equation [4.1.1.2], each face of the stick is calculated in proportion to the exposed time and by adding all the values of the exposed surface area, the overall total surface areas of the sticks can be obtained. The longer the duration of burning, the smaller the exposed surface area will be.

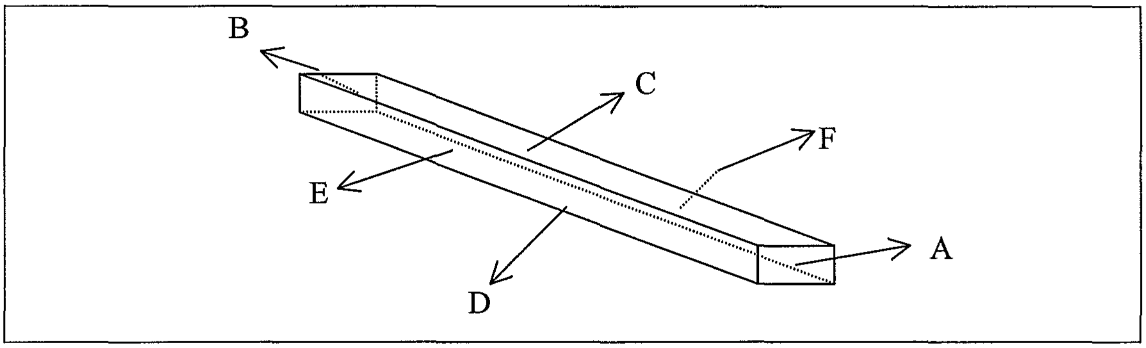


Figure 4.1.2.2: Divided faces of a typical wood stick.

To obtain the number of sticks required to make up the above arrangement in a 1 m^2 floor area so that the value of the surface area can be calculated, the equation below is used.

$$nS = 1000$$

$$S = \frac{1000}{n} \qquad [4.1.2.1]$$

where n is a constant number.

S is the value of the centre to centre spacing, (mm).

Therefore,

$$\text{the number of sticks required} = n^2. \qquad [4.1.2.2]$$

However, to be able to use both equation [4.1.2.1] and [4.1.2.2], the value of the stick thickness, D must be less than the value of the centre to centre spacing, S (ie. $D << S$).

Table 4.1.2.1 below shows the summarized number of sticks required, calculated using both equation [4.1.2.1] and [4.1.2.2], with a specific value of centre to centre spacing.

n	Spacing, S (mm)	Number of Sticks, n^2
1	1000	1
2	500	4
4	250	16
5	200	25
8	125	64
10	100	100
20	50	400

Table 4.1.2.1: Number of sticks required to make a 1 m^2 floor area with a specific value of centre to centre spacing.

Two types of combination are considered in the investigation on how the surface areas affect the heat release rate of the wood sticks in the above arrangement. These combinations are:

(a) Different stick thickness with uniform centre to centre spacing.
(b) Uniform stick thickness with different centre to centre spacing.

For combination (a) where the centre to centre spacing is kept uniform by changing the sticks' thickness, it is found that the number of sticks required to make up the 1 m^2 floor area remained the same. However, due to the decreasing value of the sticks' thickness, the surface areas exposed to the fire will decrease as well. By looking at Figures 4.1.2.3 (a) to (e), it is found that the value of the heat release rate and the duration of burning decreased when the value of the stick thickness decreased.

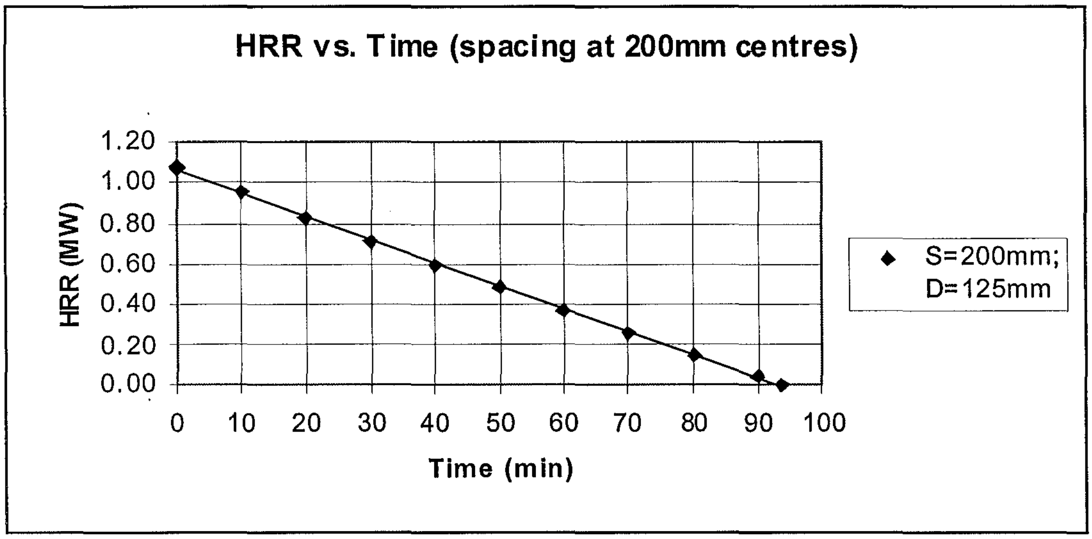


Figure 4.1.2.3 (a): HRR vs. Time graph with S = 200 mm and D = 125 mm.

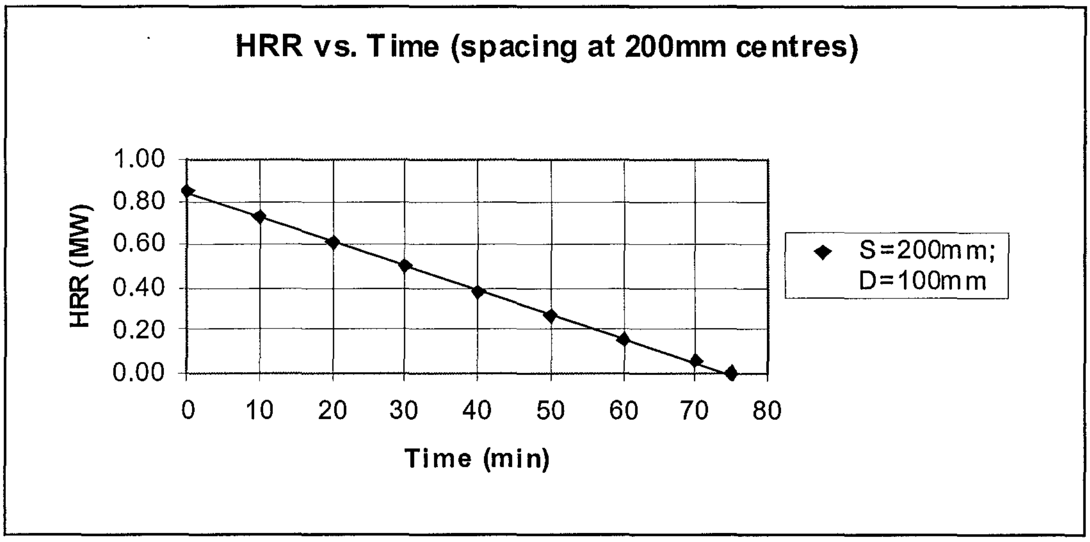


Figure 4.1.2.3 (b): HRR vs. Time graph with S = 200 mm and D = 100 mm.

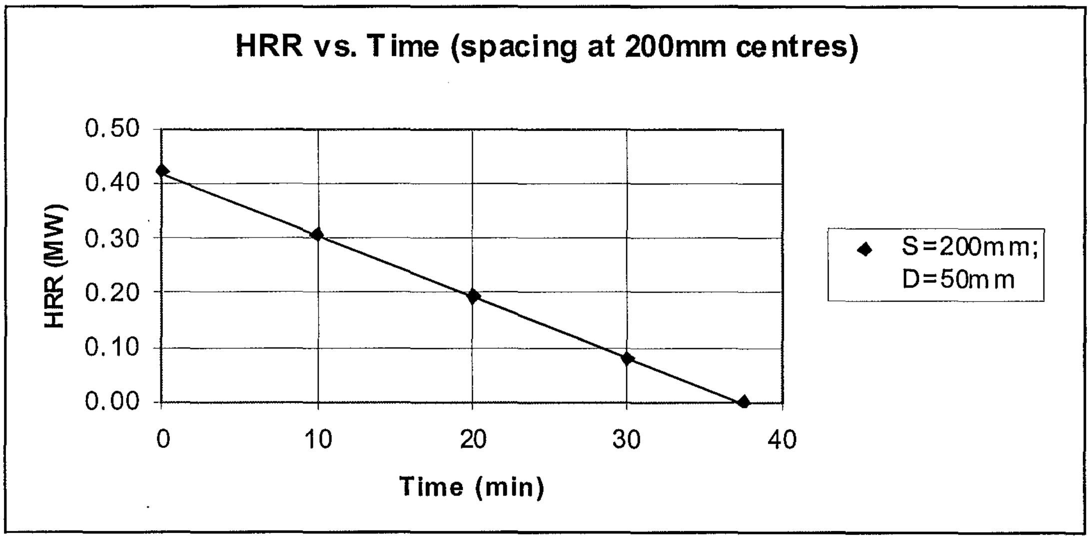


Figure 4.1.2.3 (c): HRR vs. Time graph with S = 200 mm and D = 50 mm.

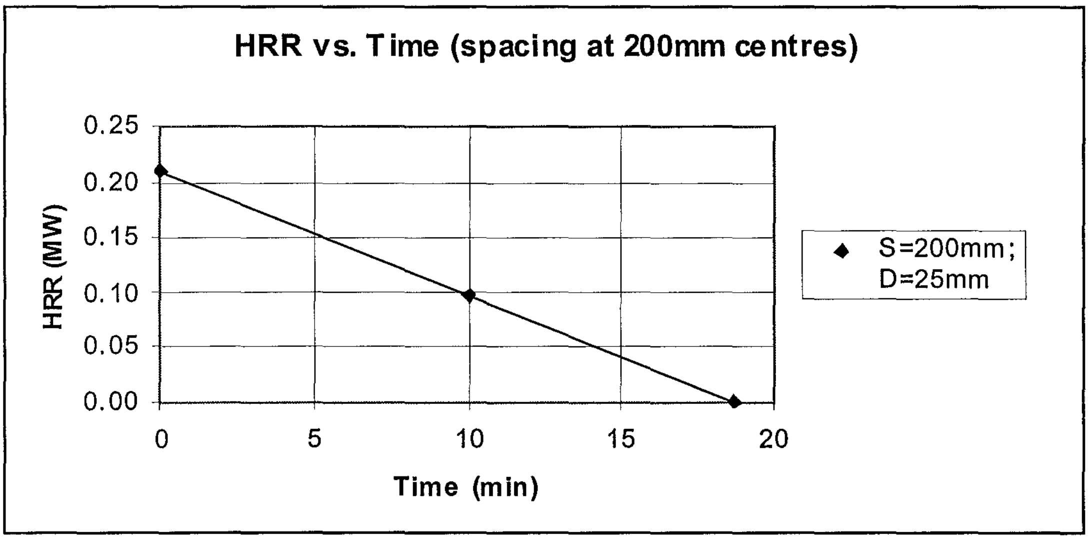


Figure 4.1.2.3 (d): HRR vs. Time graph with $S = 200$ mm and $D = 25$ mm.

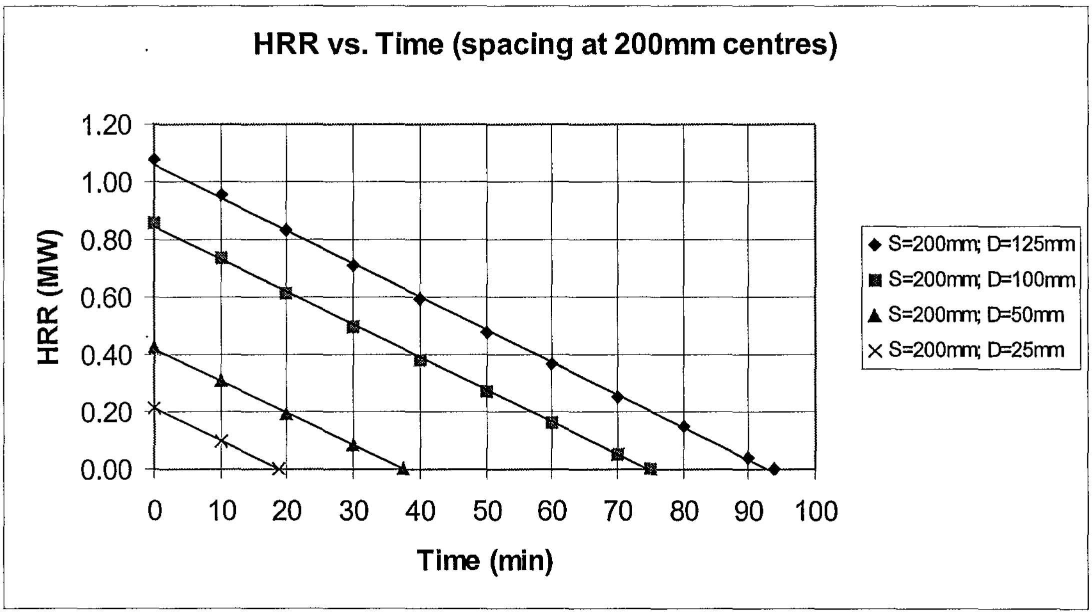


Figure 4.1.2.3 (e): HRR vs. Time graph for different value of stick thickness with uniform centre to centre spacing.

However for combination (b), keeping the sticks' thickness uniform and changing the centre to centre spacing, it is found that the number of sticks required to make up the 1 m^2 floor area decreased, with the value of the centre to centre spacing increasing. This means that the surface areas exposed to the fire will decrease as well. By looking at Figures 4.1.2.4 (a) to (e), it is found that the value of the heat release rate decreased with the increased value of the centre to centre spacing. However the duration of burning remained the same for all the four situations investigated.

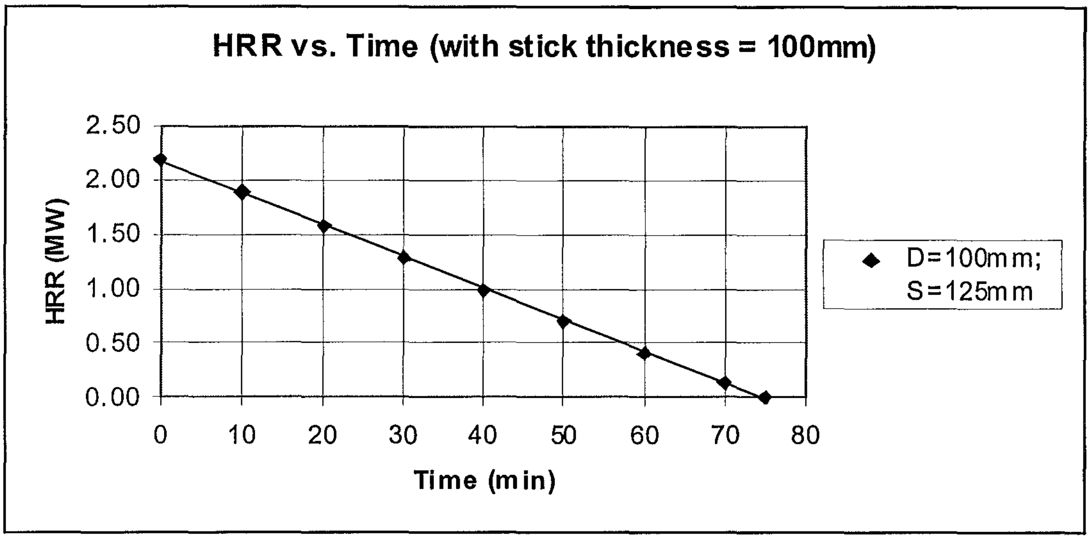


Figure 4.1.2.4 (a): HRR vs. Time graph with D = 100 mm and S = 125 mm.

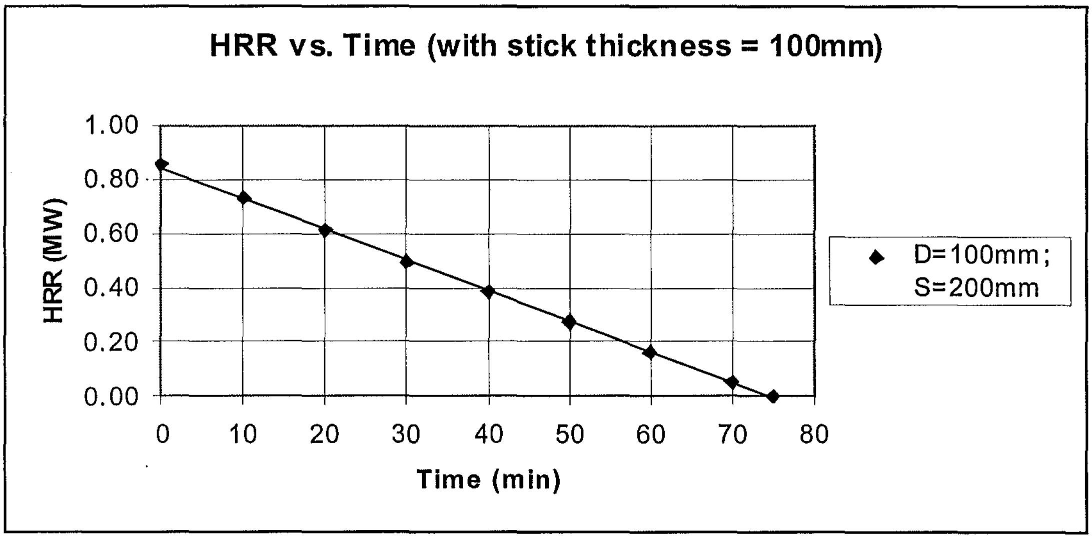


Figure 4.1.2.4 (b): HRR vs. Time graph with D = 100 mm and S = 200 mm.

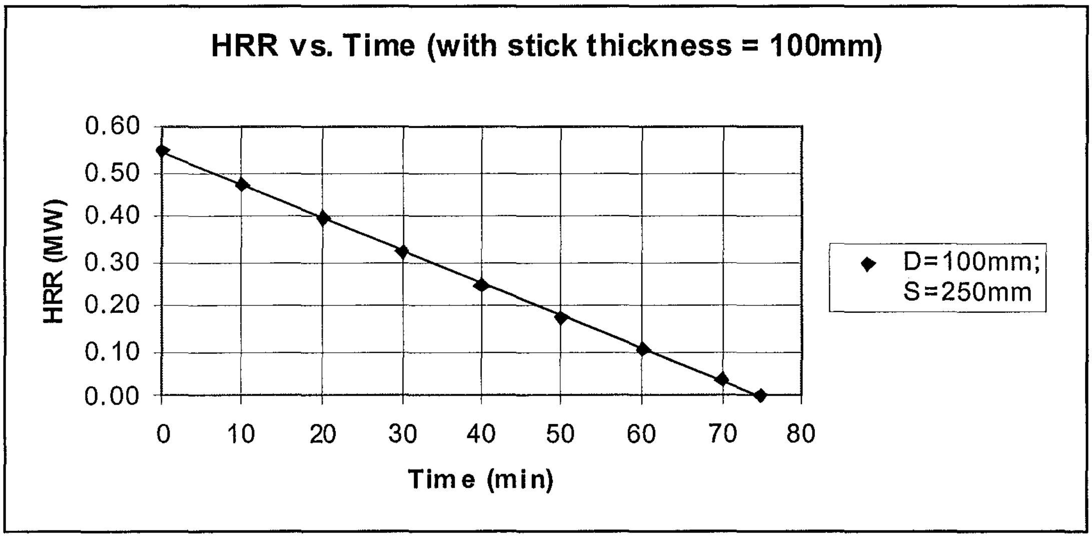


Figure 4.1.2.4 (c): HRR vs. Time graph with $D = 100$ mm and $S = 250$ mm.

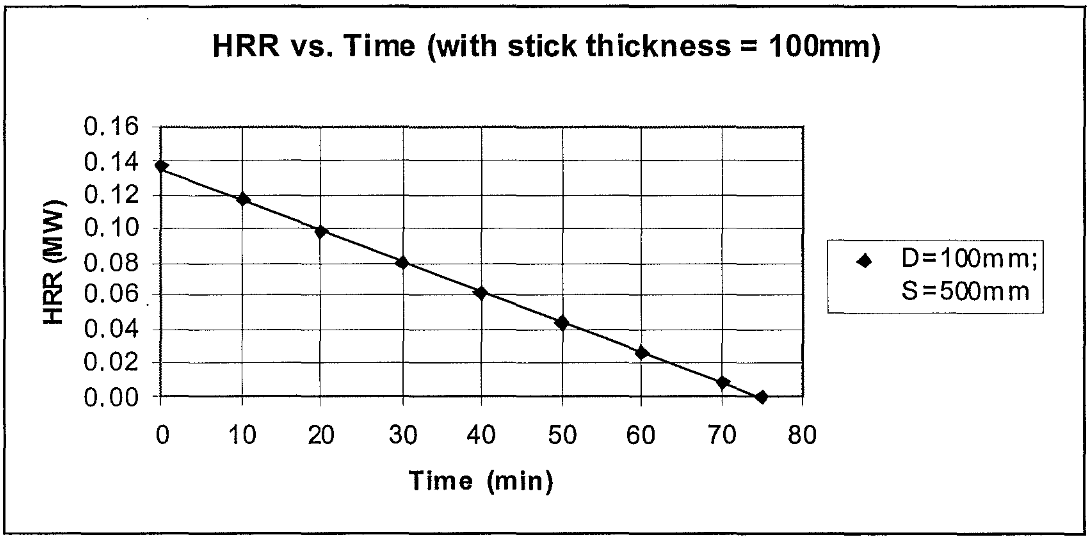


Figure 4.1.2.4 (d): HRR vs. Time graph with $D = 100$ mm and $S = 500$ mm.

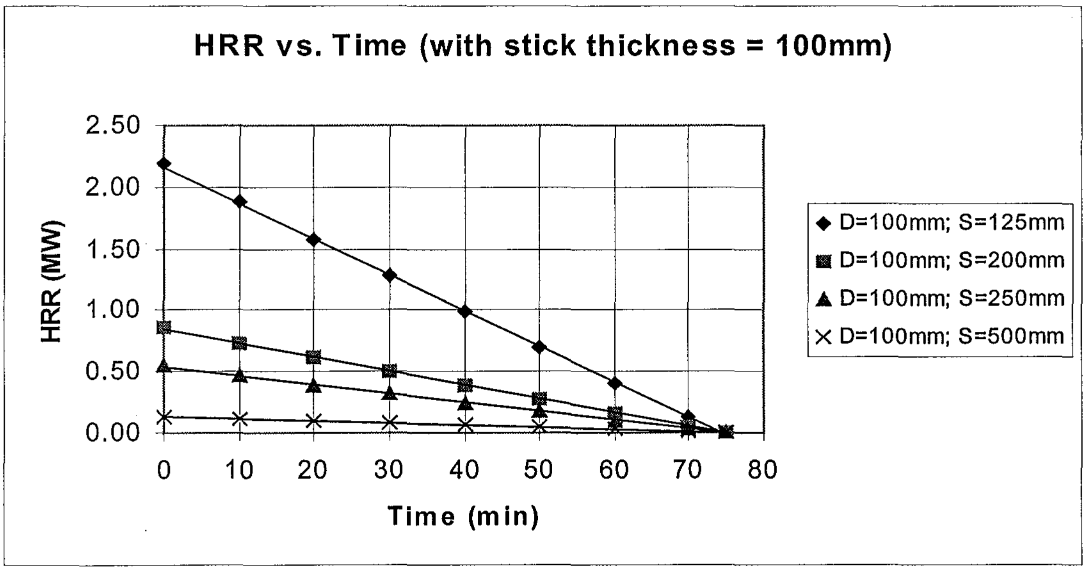


Figure 4.1.2.4 (e): HRR vs. Time graph for uniform value of stick thickness with different centre to centre spacing.

By looking at the above results, when the stick thickness or the number of the sticks required decreased, which means the value of the surface areas of the sticks exposed to the fire became smaller, the value of the heat release rate decreased as well. Therefore, it is found that the heat release rate is a function of the surface area exposed. For combination (a), the duration of burning decreased when the stick thickness decreased, but for combination (b), the duration of burning remained unchanged when the stick thickness is uniform. This means that the duration of burning is a function of the thickness of the sticks. Therefore, in conclusion, for wood sticks, the more surface area exposed to the fire, the higher the heat release rate, and the thicker the sticks, the longer time it needed to complete the burning.

4.1.3 Effects of Surface Area on HRR for Cube Blocks

In the case of the burning cube blocks, once again the surface area of the cube exposed to fire is determined by dividing it into a number of faces shown in Figure 4.1.3.1. The next step is to calculate the area of the faces exposed by using equation [4.1.1.2]. The overall total surface areas of the cube can be obtained by adding all the values of the exposed faces.

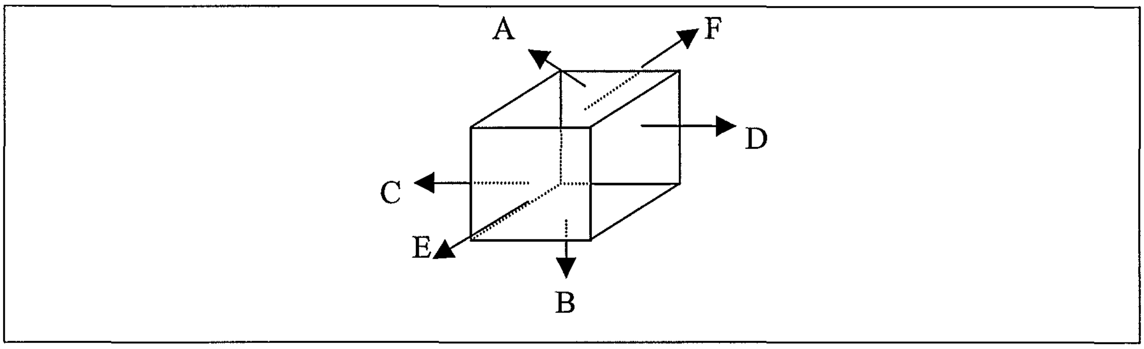


Figure 4.1.3.1: Divided faces of a typical wood cube block.

Figure 4.1.3.2 shows an example of the result of the heat release rate when a 100 mm cube block is burned during a post-flashover fire.

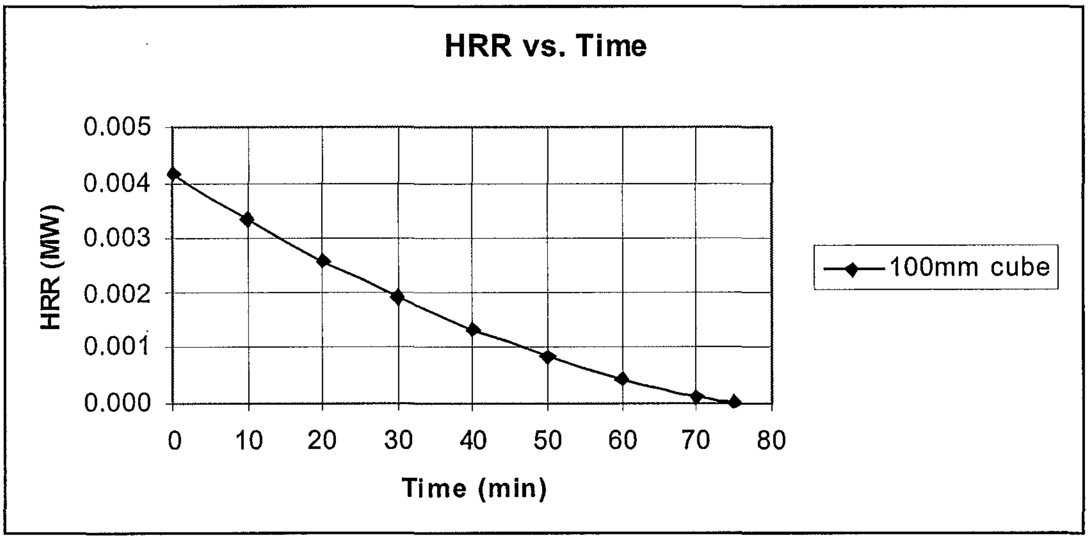


Figure 4.1.3.2: HRR vs. Time graph for a 100 mm wood cube block.

Unlike the case of the wood sticks, from Figure 4.1.3.2 it can be seen that the heat release rate for the cube block is not proportional to the duration of burning. However, this result can be justified and explained by looking at a simple burning cube block with all its faces exposed to the fire. This justification is possible by using the fact that the heat release rate is a function of the surface area exposed, mentioned in Section 4.1.2 above.

Let us say the cube block exposed to the fire has a volume of 100 mm x 100 mm x 100 mm. Therefore, by using equation [4.1.1.2], with all its six faces exposed to the fire with the regression rate of 40 mm/hr, the total overall surface areas exposed initially will be 6×10^4 mm^2. If the heat release rate is proportional to the duration of burning, by the time the cube block is burned down to a volume of 50 mm x 50 mm x 50 mm, the surface areas left are supposed to be half of the original value which is 3×10^4 mm^2. However, the true surface area left is only 1.5×10^4 mm^2, which is only about a quarter of the original value. Therefore, the HRR vs. Time graph shown for the cube block is in fact a curve line and not a straight line.

In conclusion, the burning behaviour of the wood cube blocks is different from the wood sticks and shows that the surface area left is not proportional to the time exposed.

4.1.4 Effects of Surface Area on HRR for Wooden Spheres

Unlike from the wood sticks and the wood cube blocks, the wooden spheres will be burnt from all directions due to their shape. In this case, the surface area of the sphere exposed to fire is determined by

$$A = [\pi \times (D_{sp} - 2\tau)^2] / 4 \qquad \text{m}^2 \qquad [4.1.4.1]$$

where A is the surface area exposed to the fire, (m^2).

π is equal to 3.142.

D_{sp} is the diameter of the sphere, (m).

τ is the thickness of fuel burned with time, (m), given by $\tau = \dot{v}_p \times t$.

where $\dot{v}_p$ is the regression rate, (m/s).

t is the time exposed, (s).

Figure 4.1.4.1 shows the result of the heat release rate affected by the surface area exposed when a 100 mm sphere is burned during a post-flashover fire.

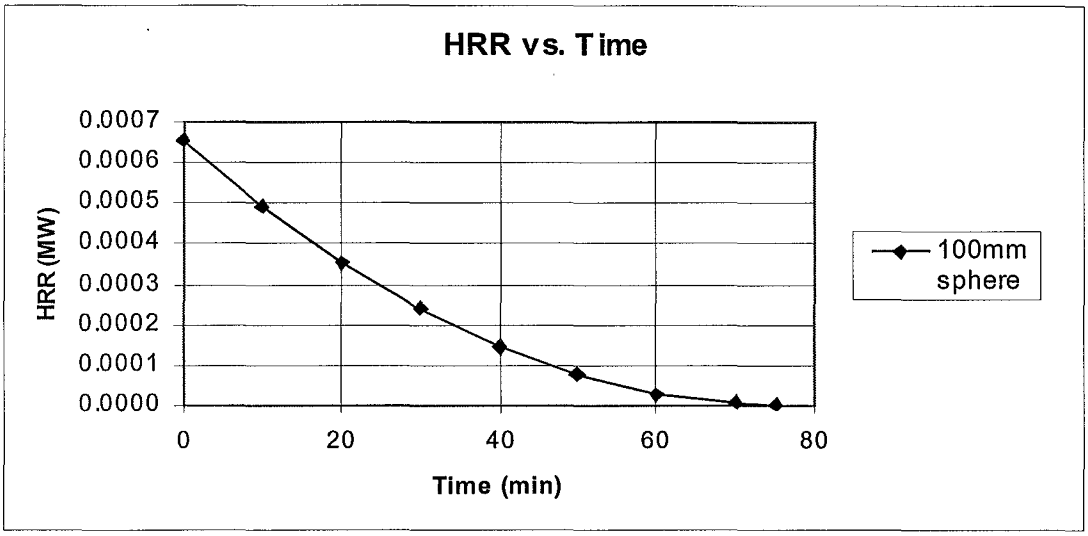


Figure 4.1.4.1: HRR vs. Time graph for a 100 mm wood sphere.

From Figure 4.1.4.1, it can be seen that the heat release rate for the sphere is not proportional to the duration of burning. Again this situation is the same as the burning of the wood cube blocks.

As for the cube block, when a sphere with a diameter of 100 mm is exposed to the fire, by using equation [4.1.4.1], with the regression rate of 40 mm/hr, the total overall surface area exposed at initial will be 7854 mm^2. If the heat release rate is proportional to the duration of burning, by the time the sphere is burned down to a diameter of 50 mm, the surface areas left are supposed to be half of the original value which is 3927 mm^2. However, the true surface area left is only 1963.5 mm^2, which is only about a quarter of the original value. Therefore, the HRR vs. Time graph shown for the sphere is a curved line, just like a burning cube block.

In conclusion, the burning behaviour of the sphere has the same characteristics as the wood cube blocks, and it shows that the surface area left is not proportional to the time exposed.

4.2 Thermoplastic Materials

4.2.1 Proposed Model to Calculate the HRR

In order to calculate the heat release rate of thermoplastic materials, the most important parameters needed are the bulk density and the net calorific value of the material, the mass loss rate per unit area, and the dimension and the mass of the material.

As mentioned in Section 3.2.3, the burning rate of thermoplastic materials does not depend on the surface regression rate, and no equation has been proposed for them as for the wood materials, therefore the value of the regression rate of the thermoplastic materials is calculated by dividing the mass loss rate per unit area with the value of bulk density. As most of the upholstered furniture is made of polyurethane material, the density and the net calorific value for this material will be used for the furniture in this report, which are 37 kg/m^3 and 35.7 MJ/kg respectively (Denize, 2000, in preparation). Besides the upholstered furniture, density and net calorific value for all other thermoplastic materials used depends on the material they are made of. However, for the simplification of this report, the density and net calorific value of polypropylene, which are 905 kg/m^3 and 43.2 MJ/kg respectively, will be used for all the other thermoplastic materials (see Table 3.2.3.1). For the mass loss rate per unit area, a value of 0.018 kg/s.m^2 (SFPE, 1995) will be used for all thermoplastic burning (refer to Section 3.2.3).

By knowing the value of the bulk density and the mass loss rate per unit area, the regression rate of the fuel can be estimated by

$$v_p = \frac{\dot{m}''}{\rho} \qquad \text{kg/s.m}^2 \qquad [4.2.1.1]$$

where v_p is the regression rate, (m/s).

$\dot{m}''$ is the mass loss rate per unit area, (kg/s.m^2).

ρ is the value of the bulk density, (kg/m^3).

For the thermoplastic materials, it is assumed that during the post-flashover fire, the materials will burn in a pool-like fire. Therefore, the surface area exposed is assumed to be the same as the pool area. By knowing the exposed surface area of the combustible thermoplastic fuel load during the fire, which in this case is the pool area, the mass loss rate and the heat release rate of the exposed material can be calculated. In time, the surface area exposed will be reduced according to the regression rate of the fuel.

The equation proposed to calculate the pool area is

i. For rectangle or square shape pool:

$$A_p = W_s \times D_s \qquad \text{m}^2 \qquad [4.2.1.2]$$

ii. For circular pool:

$$A_p = \frac{\pi d^2}{4} \qquad \text{m}^2 \qquad [4.2.1.3]$$

where A_p is the pool area exposed to the fire, (m^2).

W_s is the width of the surface, (m).

D_s is the depth of the surface, (m).

d is the diameter of the pool, (m).

After knowing the value of the pool area exposed, the mass loss rate can be calculated by

$$R = \dot{m}'' \text{ x } A_p \qquad \text{kg/s} \qquad [4.2.1.4]$$

where R is the mass loss rate, (kg/s).

$\dot{m}''$ is the mass loss rate per unit area, ($kg/s.m^2$).

A_p is the surface area exposed to the fire, (m^2).

The heat release rate then is simply determined as the product of mass loss rate and the net calorific value for a specific thermoplastic material.

$$Q = R \times \Delta H_c \qquad \text{MW} \qquad [4.2.1.5]$$

where Q is the heat release rate, (MW).

R is the mass loss rate, (kg/s).

ΔH_c is the net calorific value, (MJ/kg).

It must be noted that this proposed model of the thermoplastic materials is for fuel burning during the post-flashover fire where it is assumed that all the fuel is ignited and the surface areas exposed are the same as the pool area.

Table 4.2.1.1 below shows the summary of how the heat release rate is calculated with the value of pool area known.

Density, ρ (kg/m^3)	Regression Rate, v_p (m/s)	Mass Loss Rate Per Unit Area, m'' ($kg/s.m^2$)	Pool Area, A_p (m^2)	Mass Loss Rate, R (kg/s)	Net Calorific Value, ΔH_c (MJ/kg)	HRR, Q (MW)
Given	m'' / ρ	Given	Equation [4.2.1.2] or [4.2.1.3]	$m'' \times A_p$	35.7 (polyurethane) or 43.2 (polypropylene)	$R \times \Delta H_c$

Table 4.2.1.1: Summary of the steps in calculating the heat release rate based on the pool area exposed to fire for thermoplastic materials.

By knowing the mass of the thermoplastic fuel available, the volume of the fuel can be estimated by

$$V = \frac{m}{\rho} \qquad m^3 \qquad [4.2.1.6]$$

where V is the volume of the fuel, (m^3).

m is the mass of the fuel, (kg).

ρ is the density of the fuel, (kg/m^3).

With the value of the volume known, the thickness of the pool can be estimated which in turn can predict the time needed to burn the fuel with a certain pool area. The thickness of the pool is calculated by

$$D_p = \frac{V}{A_p} \qquad \text{m} \qquad [4.2.1.7]$$

whereas the duration of burning for the pool is

$$t_d = \frac{D_p}{v_p} \qquad \text{s} \qquad [4.2.1.8]$$

where. D_p is the thickness of the fuel, (m).
V is the volume of the pool, (m^3).
A_p is the surface area exposed to the fire, (m^2).
t_d is the duration of burning, (s)
v_p is the regression rate, (m/s).

It must be noted that the duration of burning for the thermoplastic fuel calculated from equation [4.2.1.8] is the burning time without any intervention, assuming the combustible materials burned in a pool-like fire (as during post-flashover fire).

4.2.2 Effects of Pool Area on HRR for Thermoplastic Pool

Since most thermoplastic materials melt when subjected to fire environments, this behaviour may affect the burning behaviour of thermoplastic. During the development of the fire, the melted plastic fed a growing pool fire underneath the object. Therefore, due to the mass transportation from the surface of the solid plastic to the liquid-like melt pool, this behaviour creates an extra difficulty to investigate the effects of the thermoplastic material surface area on the heat release rate.

However, for post-flashover fire, it is assumed that all the solid plastic materials will become the liquid-like melt pool underneath the object. Therefore, the width of the melt pool and area of the pool are important and considered to be the area exposed to fire for the thermoplastic material during the post-flashover fire.

By considering the pool fire to be in steady state, the simple model showing the effects of the pool area on the outcome of the heat release rate is shown in Figure 4.2.2.1.

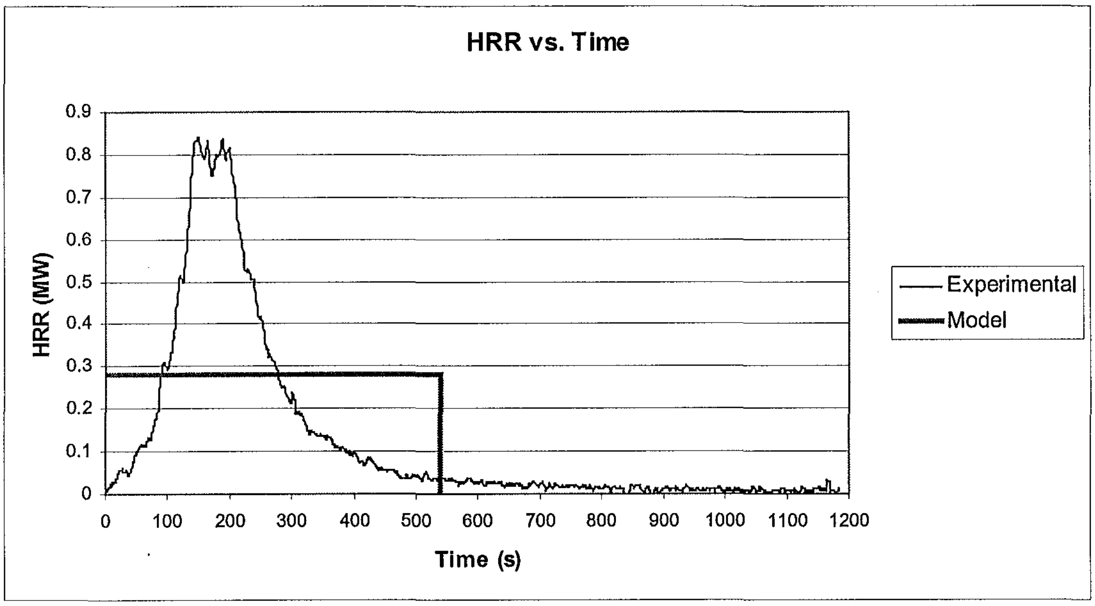


Figure 4.2.2.1: Comparison between experimental data from Denize (2000, in preparation) and model result for a typical upholstered furniture.

Based on the model result, it is assumed that the fuel in the pool will be consistent during the cycle of the burning, and gone when the duration of the burning is reached. The area underneath the graph represents the energy released, and it is a good comparison with the experimental data (Denize, 2000, in preparation), provided the value of density, net calorific value and the mass loss rate per unit area are known. For simplification, this proposed model is used throughout the report for the thermoplastic fuels and is a reasonable method in calculating the heat release rate, which is affected by the exposed surface area.

However, for thermoplastic materials burning inside a fire compartment, this proposed model will underestimate the heat release rate and overestimate the burning period, as it does not take into account the radiation inside the compartment.

Therefore, extra care is needed when one uses the heat release rate of the thermoplastic fuels predicted by the proposed model above for other purposes.

Instead, the previous method of predicting the shape of the full-scale heat release curves presented by Ames, Babrauskas and Parker (1992) should be considered. This method simplified the heat release curves into a triangular representation, and the base width, t_b, which is the duration of burning, is calculated by

$$t_b = \frac{C_3 m \Delta h_c}{\dot{q}_{fs}} \quad \text{s} \qquad [4.2.2.1]$$

where m is the combustible mass of the specimen, (kg).

$\dot{q}_{fs}$ is the peak full-scale heat release rate (MW).

Δh_c is the effective heat of combustion, (MJ/kg).

C_3 is defined as ~ 1.3 for wood frames.

~ 1.8 for metal frames and plastic frames.

5. EFFECT OF VENTILATION ON HRR OF FUEL

After flashover, the behaviour of the fire changes dramatically. All the exposed combustible surfaces started to pyrolize, producing large quantities of combustible gases, which burn, provided there is sufficient oxygen. Therefore, in a typical fire compartment, during post-flashover, the fire changes from fuel controlled to ventilation controlled. This is because at that stage of fire, the quantities of burning fuel exceed the available ventilation which is needed to support the burning. In other words, the rate of combustion during post-flashover fire depends on the size and shape of ventilation openings.

For example, if a fire compartment having a certain window size and shape contains one wooden table, the rate of burning of the table will probably be controlled by the surface area of the table. This is because there is enough air available to support the burning of a single table. On the other hand, if the fire compartments contain ten or more tables, it is likely that the rate of burning of the tables will be controlled by the dimensions of the window through which the air necessary for the combustion of the tables can be supplied. Therefore, at some point, there is a limit called the ventilation limit, where the available air inside the compartment no longer supports the burning. Beyond the ventilation limit, all the flames extend out the windows, and additional combustion tends to take place where the hot unburned gaseous fuels mix with the outside air.

The corresponding ventilation controlled heat release rate, Q_{vent}, (ventilation limit), can be calculated by (Buchanan, 1999)

$$Q_{vent} = R\Delta H_c \qquad \text{MW} \qquad [5.1]$$

where ΔH_c is the net calorific value of the fuel, (MJ/kg).

R is the mass loss rate of the fuel, (kg/s), given by $R = 0.092 A_v \sqrt{H_v}$ (Kawagoe, 1958).

where A_v is the area of the window opening, (m^2).

H_v is the height of the opening, (m).

In the case of a fire compartment full of combustible fuel load, the value of the heat release of the fuel is going to be higher than what is allowed for due to the ventilation limit. Therefore, there are two options available in describing the situation:

a) Beyond the ventilation limit, the fuel is assumed to be burning outside the windows or
b) Assume the amount of energy beyond the ventilation limit will be burned first inside the fire compartment (nearer to the windows), E1, then the energy release by the fuel under the ventilation limit will take place, E2.

Figures 5.1 and 5.2 below illustrate the concepts presented by options (a) and (b).

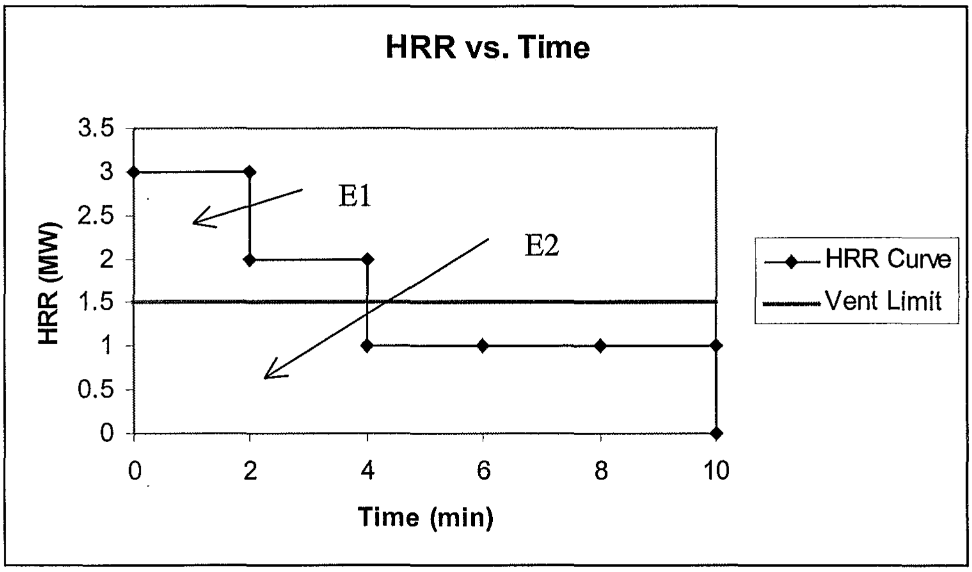


Figure 5.1: Example of a HRR vs. Time graph showing E1 and E2 for option (a).

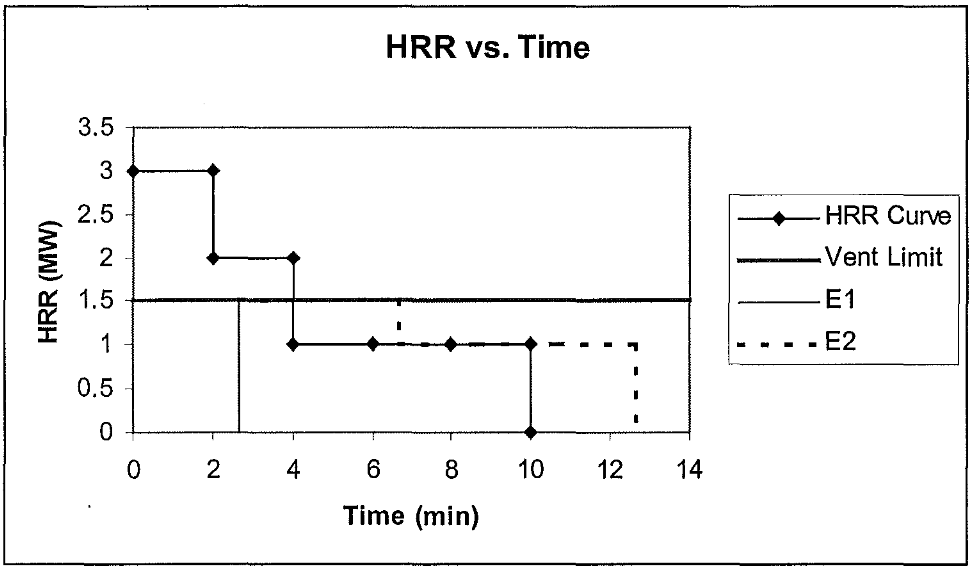


Figure 5.2: Example of a HRR vs. Time graph showing E1 and E2 for option (b).

Option (a) can normally be seen in most fully-developed fires, where flames project from the windows. The rate of fuel pyrolysis is greater than can be burnt by the available air supply inside the compartment, resulting in flames burning from openings as the unburnt gases obtain access to outside air.

Option (b) can be described based on the experiment by Kirby (1994), where while burning wood cribs in a large scale compartments, although the fire was set at the end of the compartment, the fire spread forward to the front of the compartment where the ventilation was. The cribs nearer to the ventilation at the front burned first, and the fire slowly spread to the back of the compartment. Kirby's (1994) results showed that the temperature of the cribs nearer to the ventilation was higher than the temperature of the cribs at the end of the compartment. Therefore, this finding support the idea in option (b), which suggest that the amount of fuel which is beyond the ventilation limit will be burned first as it is nearer to the windows. Then the fuel further away from the windows will be burned, which in this case represent the burning fuel under the ventilation limit.

However, the real situation of the energy release inside a fire compartment with a certain window size and shape might be between E1 and E2 in option (b). This is because although the concept of the fuel nearer to the ventilation being burned first is acceptable, the fuel further away from the ventilation might be pyrolyzing, if not burning. This is especially true for thin fuel such as pieces of paper lying around inside the compartment.

More details of these options are discussed in Chapter 8.

6. HRR OF FURNITURE BASED ON EXPOSED SURFACE AREA

In Chapter 4, the proposed model based on the surface area exposed to fire for solid wood materials and thermoplastic materials has been discussed. Besides that, the effects of surface area of the simple geometrical objects such as wooden sticks, wooden cube blocks, wooden spheres and plastic materials on heat release rate have also been examined.

It was found that the heat release rate of a certain object is a function of the surface area exposed to fire, whereas the duration of burning is a function of the thickness of the object. Therefore, from here, it could been see that the surface area exposed to fire has a great impact on the outcome of the heat release rate.

In Chapter 4, only objects with a simple geometry have been investigated. However, in order to understand the behaviour of more complicated objects such as furniture which can be found in most of the building occupancies, this chapter will look at the effects of the surface area of each individual piece of furniture on the heat release rate, assuming a constant regression rate on all exposed surfaces, during a post-flashover fire.

6.1 Beds / Mattresses

Beds provide high fuel loads during a fire, especially in residential households, motels, hotels and other building occupancies which are used for sleeping purposes. However, it becomes very complicated to estimate the surface area of beds exposed to fire.

It becomes very complicated because beds do not consist of only one material but are made of several materials. These are the mattress and the wood base. The mattress is a soft good, which is constructed using polyurethane foam, covered with upholstered fabric, and has no structural components, or else has steel innersprings. The wood base which holds the mattress is normally covered by upholstered fabric and some polyurethane foam fillings. Therefore, in order to simplify the procedure so that the effect of the surface area of the beds on the heat release rate can be examined, only the upholstered materials on both the mattress and the wood base are investigated, by assuming the fire will go out as soon as the upholstered materials are gone, leaving only the wooden frame.

By using the proposed model for thermoplastic materials discussed in Section 4.2.1, the upholstered materials of the bed are assumed to be melted and burned in a pool-like fire under the bed during the post-flashover fire. Therefore, the mass and the dimension of the bed are the important measurements needed during the surveys, and the thermoplastic materials used are assumed to be polyurethane.

Figure 6.1.1 below shows an example of a single bed.

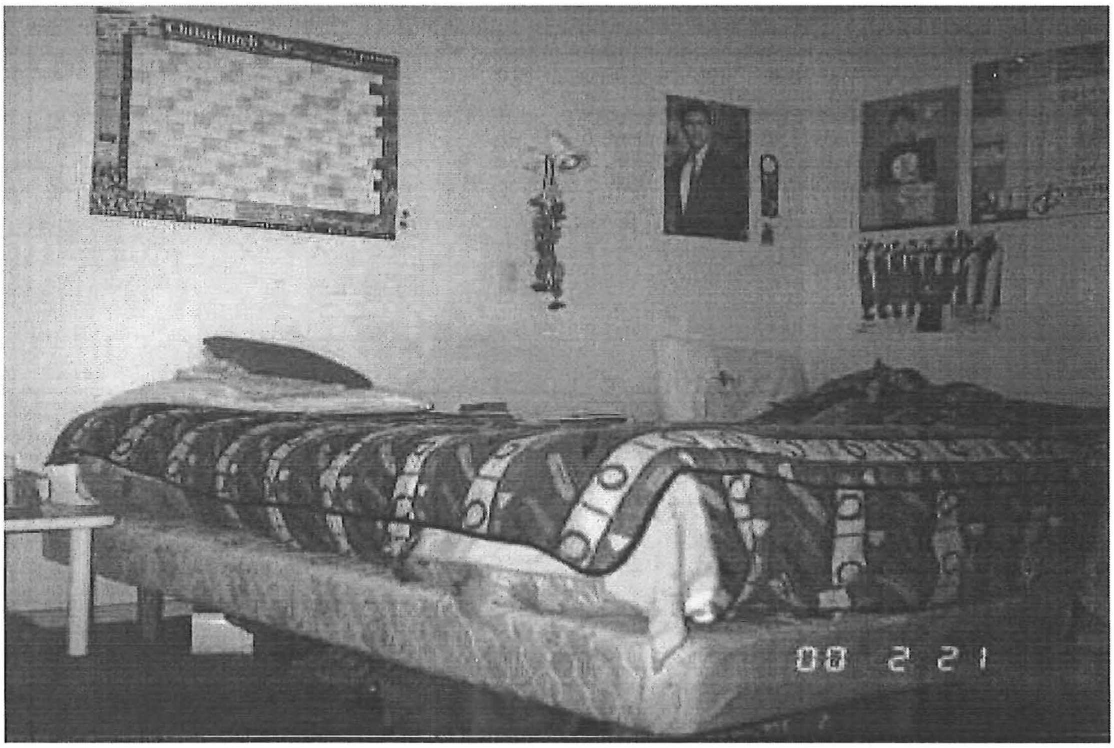


Figure 6.1.1: Single bed.

The single bed is 90 kg with approximately 45 kg of the weight being polyurethane foam. The dimensions of the bed are 1 x 2 m.

Figure 6.1.2 shows the outcome of the heat release rate of the burning of the plastic materials of the bed, using the proposed model presented in Section 4.2.1.

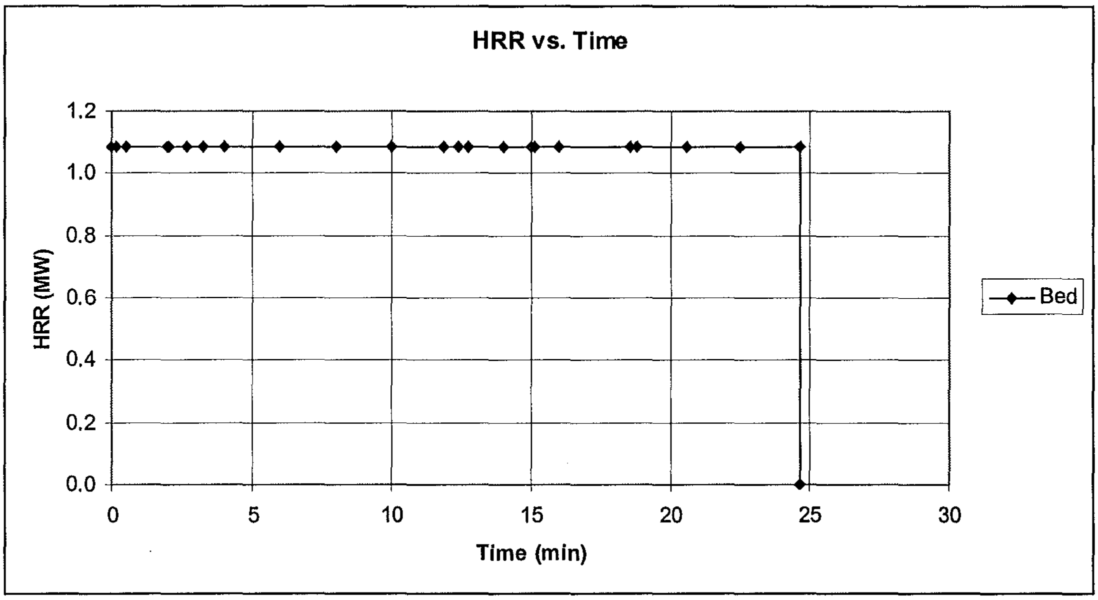


Figure 6.1.2: HRR vs. Time graph for the burning of the plastic material of a single bed.

From Figure 6.1.2, the heat release rate produced by the single bed, based on the amount of polyurethane material available in the bed, is approximately 1.1 MW. It is assumed that the value of the heat release rate of the bed will remain in steady state until all the fuel has burned away. The duration of burning of the single bed, for approximately 45 kg of polyurethane materials, is about 24.5 min.

6.2 Bookshelves

Bookshelves are normally found in offices and libraries. Only bookshelves which are made of wood are a concern here as steel bookshelves normally do not have such a high fuel load during a fire. Books and papers on the bookshelves are assumed to have the same burning characteristics as wood (Law and Arnault, 1972).

6.2.1 Bookshelf (I)

This type of bookshelf is normally found in offices, built into the wall. During the investigation of the effects of the surface area on the outcome of the heat release rate, the bookshelf is consider to be in situation

(a) 100% full.
(b) 75% full.
(c) 50% full.
(d) 25% full.

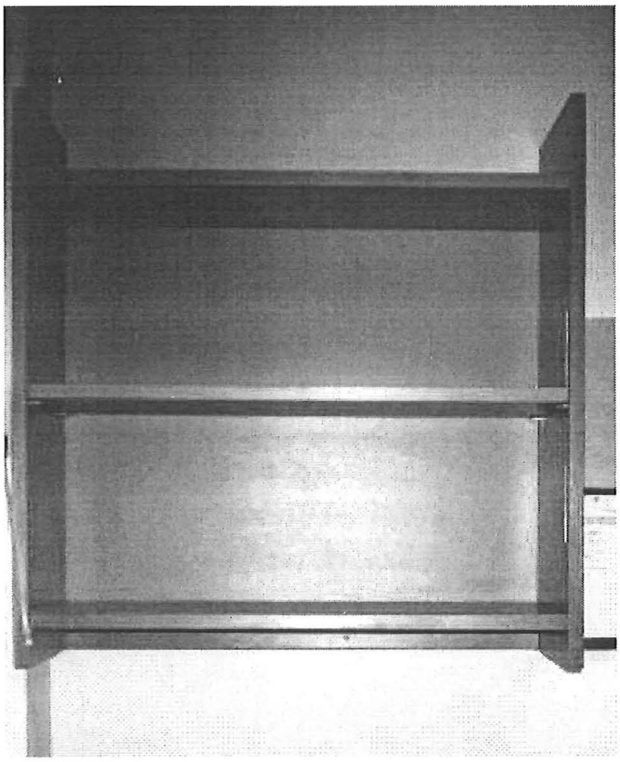


Figure 6.2.1.1: Bookshelf (I).

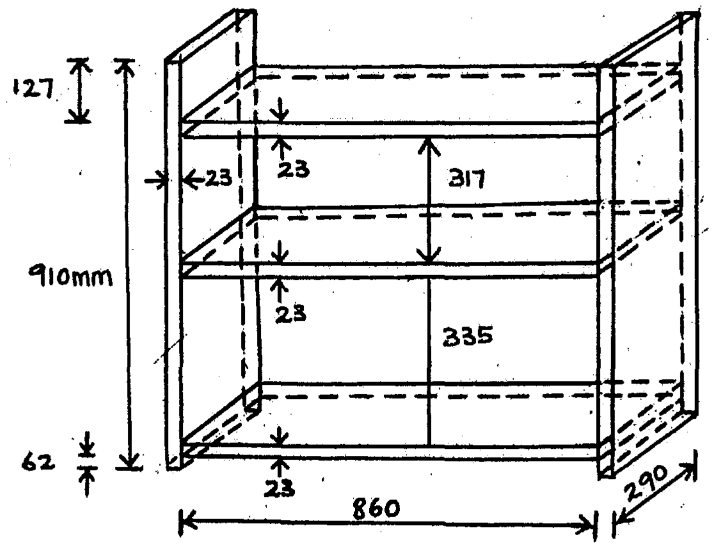


Figure 6.2.1.2: Dimensions of bookshelf (I) in mm.

For situation (a), which is 100% full, the bookshelf is considered to be a block. For situations (b) to (d), which are 75 %, 50% and 25% full, respectively, the bookshelf is divided into a smaller block (the part that contains books and papers), and other several thin pieces of wood (exposed to fire).

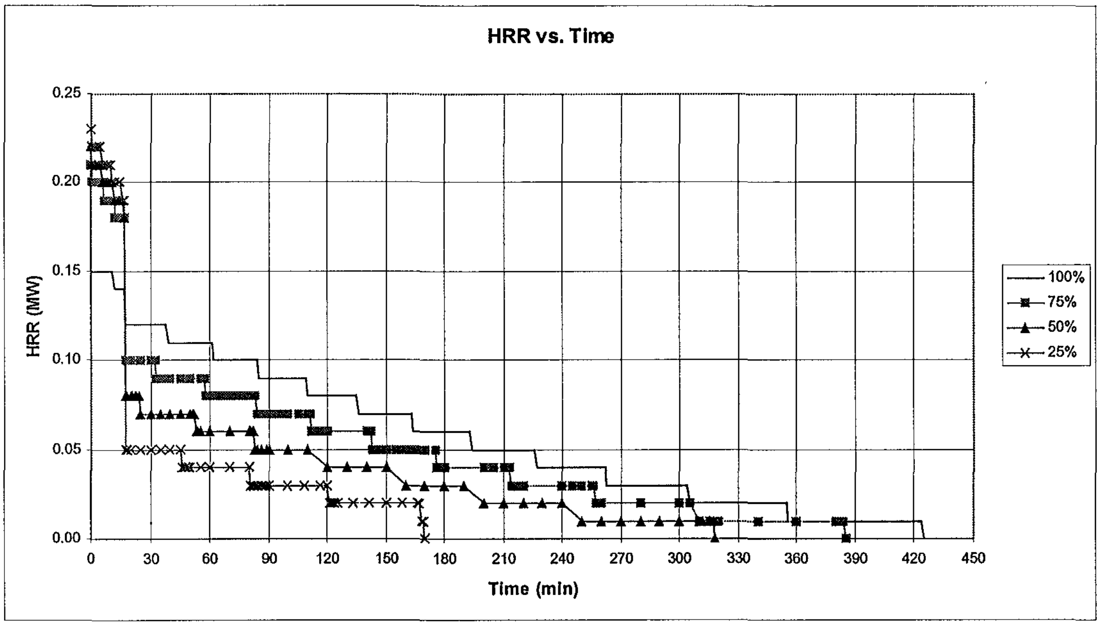


Figure 6.2.1.3:Comparison of the output of heat release rate for full and partially full bookshelves (I).

From Figure 6.2.1.3, it can be seen that the value of the heat release rate increased as the percentage of contents of the bookshelf decreased. This is because more and more surface area, which does not contain any books, is exposed to the fire. From the figure, it can also be seen that there is a large drop in the value of the heat release rate for situations 75%, 50% and 25% after approximately 18 minutes of exposure. This is due to the thinner part exposed to fire burning out more quickly. The lower value of the heat release rate after the drop represents the thicker parts, which will take more time to burn out. As the contents of the bookshelf decrease, the duration of burning will decrease as well due to the decrease in thickness of the thickest part of the bookshelf.

6.2.2 Bookshelf (II)

This type of bookshelf is a longer version of bookshelf (I). It is normally found in offices, with its back attached close to the wall. Therefore there will be no surface exposure to the fire from that side. As before, the bookshelf is considered in four situations:

(a) 100% full.

(b) 75% full.

(c) 50% full.

(d) 25% full.

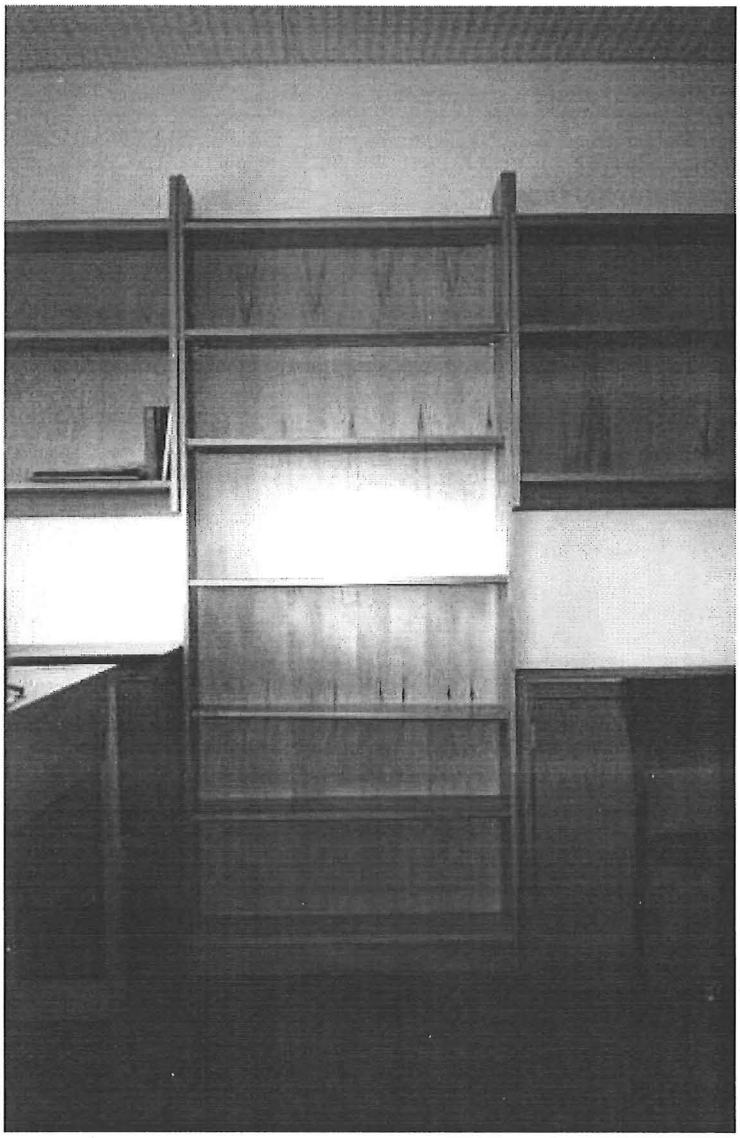


Figure 6.2.2.1: Bookshelf (II).

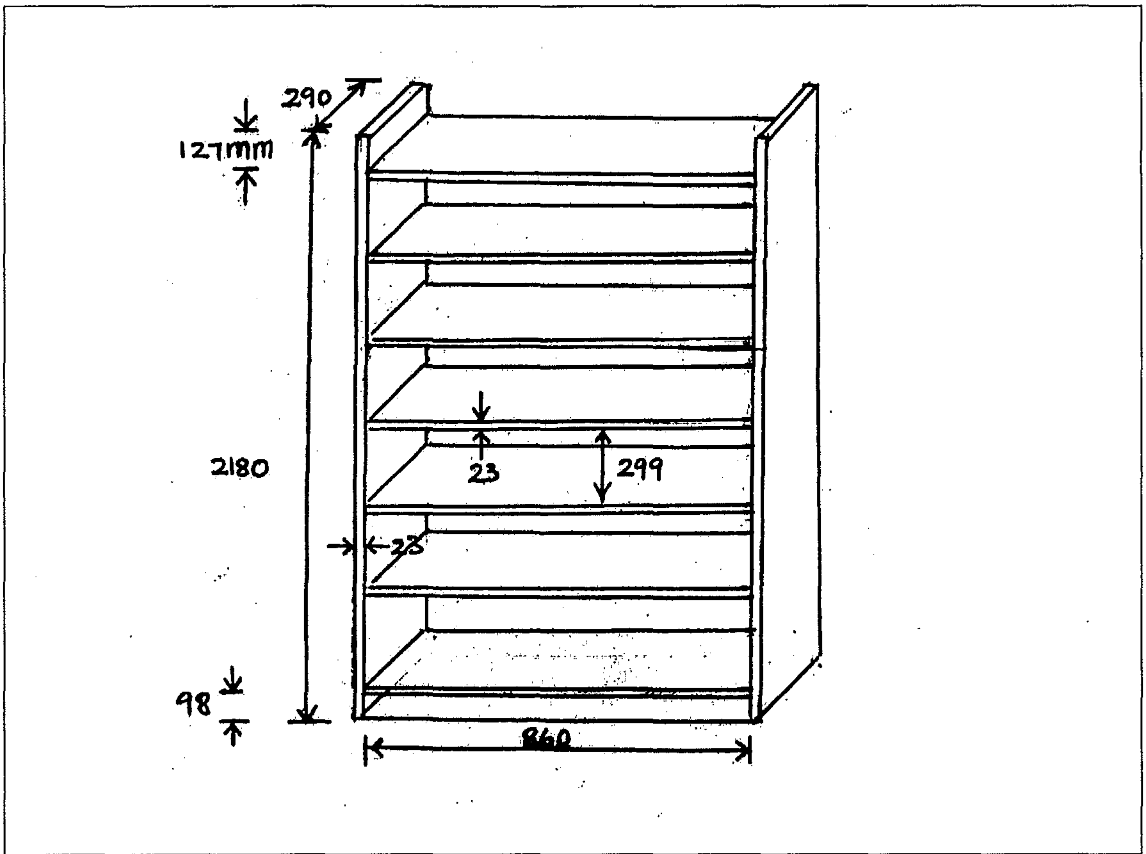


Figure 6.2.2.2: Dimensions of bookshelf (II) in mm.

As for bookshelf (I), bookshelf (II) is again divided into several parts such as a block, for the thicker part which contains books and papers, and thinner parts, which are freely exposed to fire. By using this method of division, the surface area of the bookshelf (II) exposed to fire can be easily assessed.

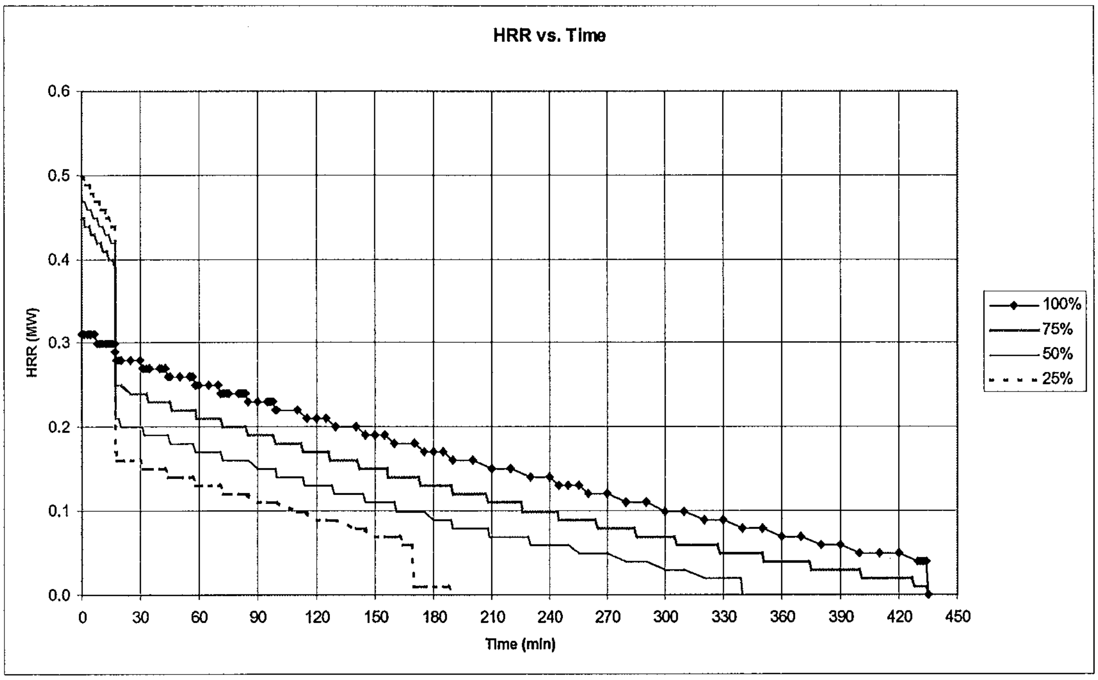


Figure 6.2.2.3:Comparison of the output of heat release rate for full and partially full bookshelves (II).

Figure 6.2.2.3 shows similar results as in Figure 6.2.1.3. The less the percentage of books, the greater the surface area exposed and the higher the value of heat release rate. The dramatic drop in the value of the heat release rate represents the burn out of the thinner parts of the bookshelf, while the duration of the burning is based on the thickest part of the bookshelf.

6.2.3 Bookshelf (III)

Bookshelf (III) is a type of bookshelf which is not only a bookshelf but also has a cupboard extension underneath it (see Figure 6.2.3.1). It is a larger version of bookshelf (I) and (II) with a cupboard underneath it. Therefore, by assuming it is fully packed with books and papers without any space left, bookshelf (III) can be divided into two large blocks, one representing the upper shelf, while the other block represents the lower cupboard.

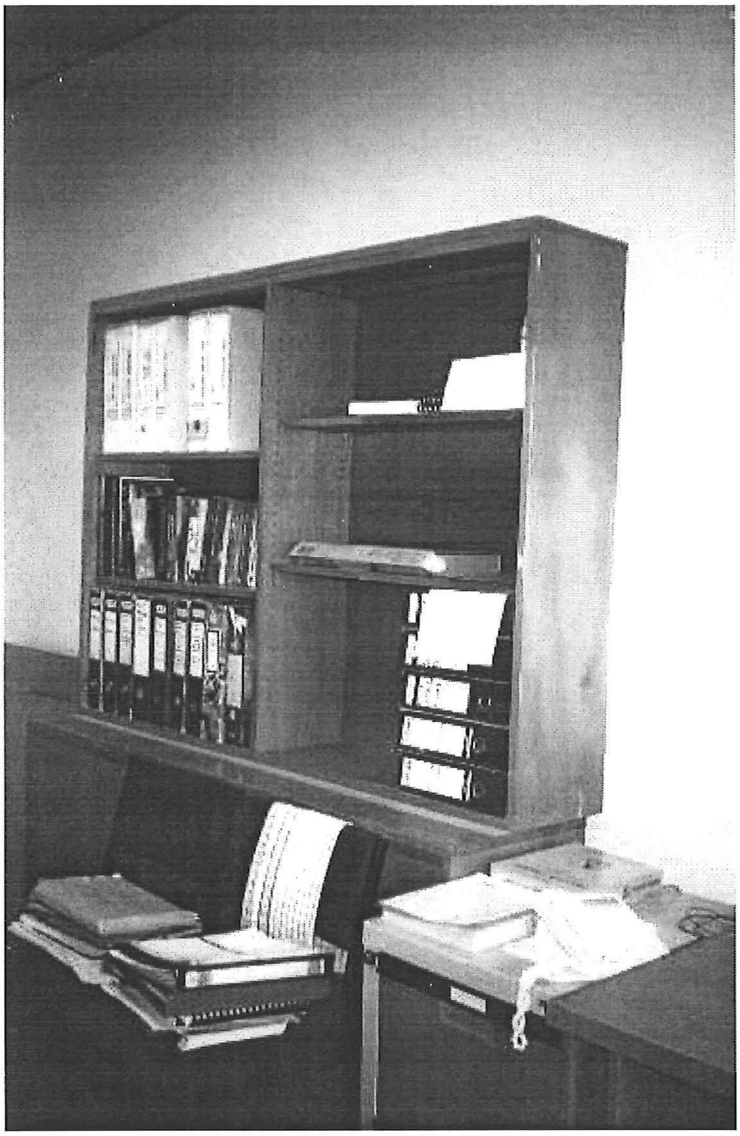


Figure 6.2.3.1: Bookshelf (III).

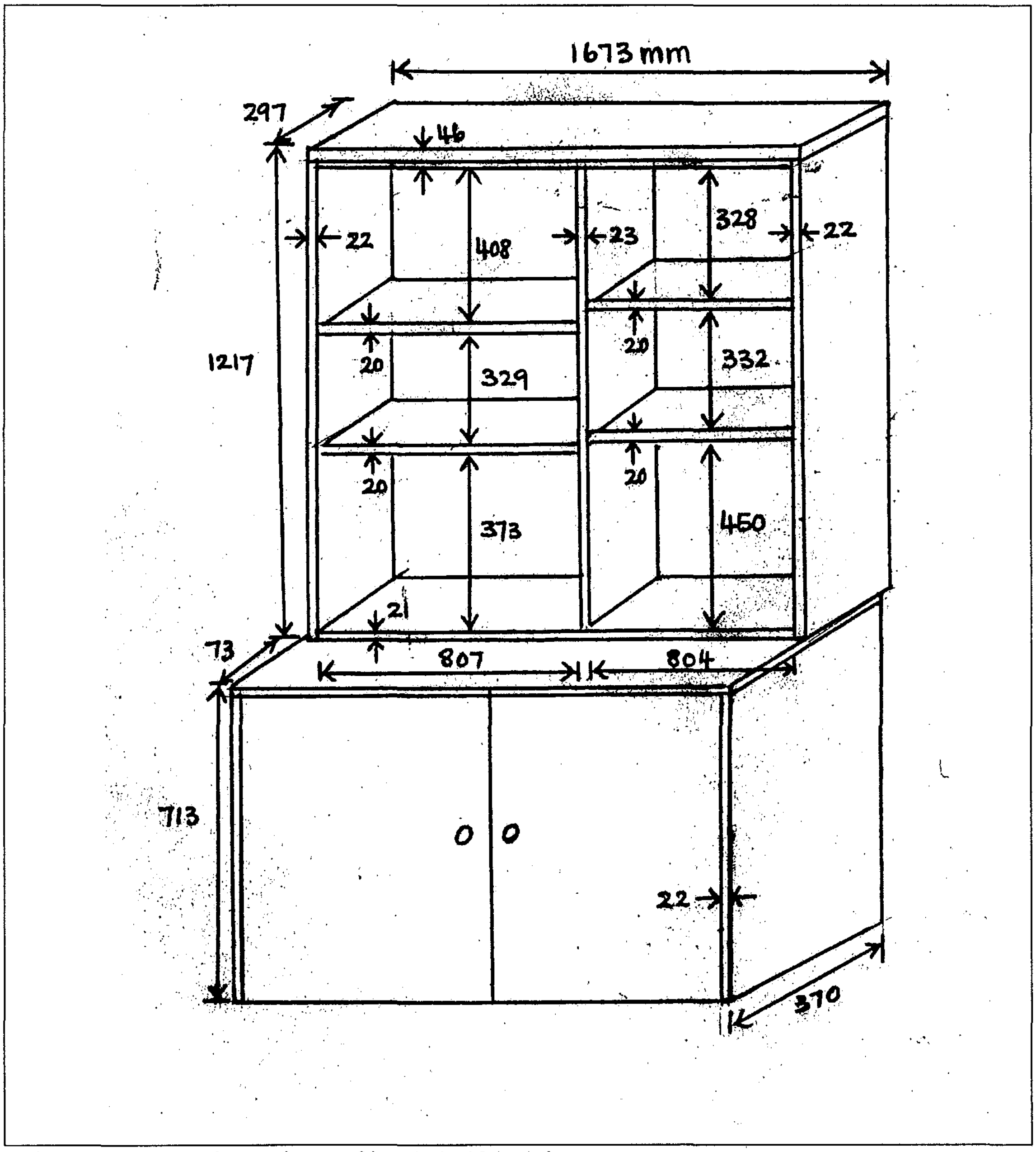


Figure 6.2.3.2: Dimensions of bookshelf (III) in mm.

For bookshelf (III), the surface area exposed to fire is based on the two large blocks.

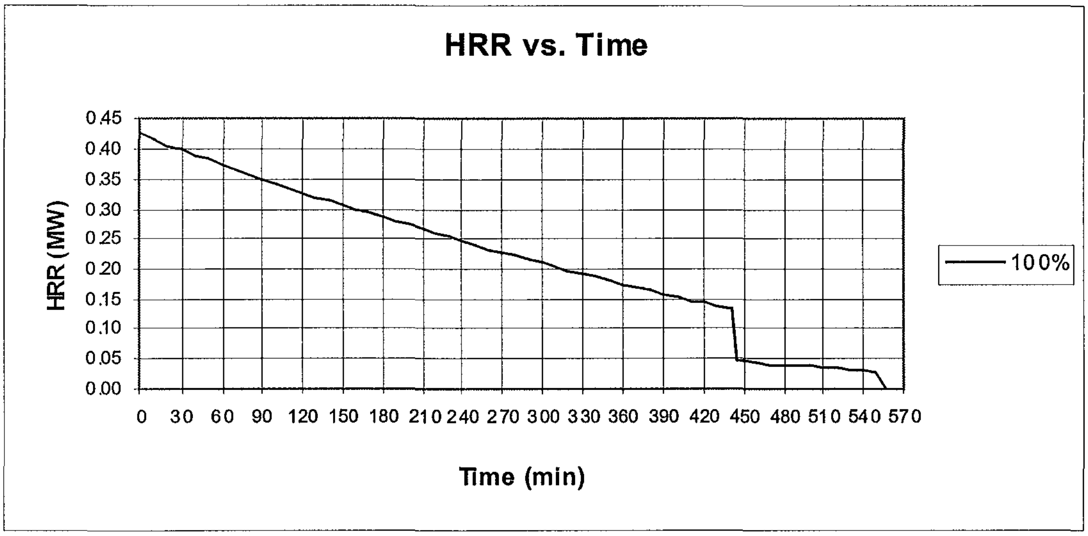


Figure 6.2.3.3: HRR vs. Time graph of bookshelf (III) with 100% full of books and papers.

The result shown in Figure 6.2.3.3 has a similar version of the outcome of heat release rate as for a wooden cube block in Section 4.1.3. The smaller block will be burned out before the larger block. The duration of burning is based on the thickness of the larger block.

6.3 Carpet

Carpets provide high fuel loads in almost every building occupancy in New Zealand, such as residential households, offices and motels. This is due to the large surface area exposed to the fire. However, the duration of burning is less compared to other thermoplastic materials due to its thickness. Carpets are made of wool and thermoplastic materials. However, for this report, only synthetic carpets are considered. Therefore, the thermoplastic material used for the carpet is assumed to be polyurethane.

Figure 6.3.1 below shows the heat release rate of a carpet of approximately 15 kg of weight and 7 m^2 of surface area exposed to fire. The value of heat release rate was 4.5 MW and remained constant until the fuel is gone, which was around 1.98 minutes.

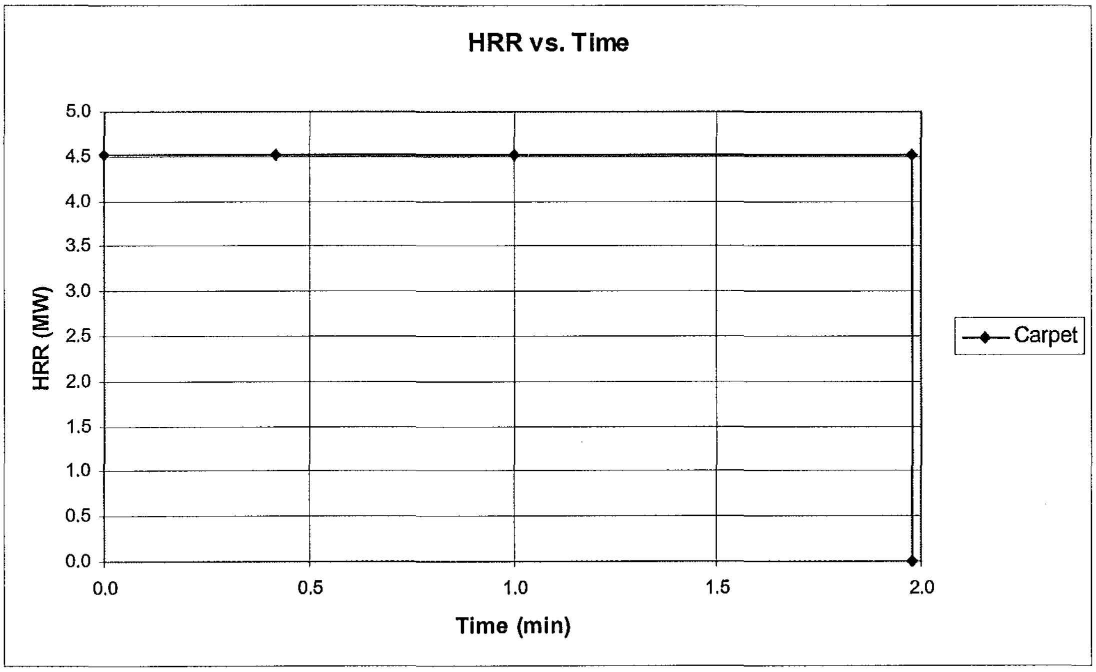


Figure 6.3.1: HRR vs. Time graph for 15 kg carpet with 7 m^2 surface area.

6.4 Computer

A computer is made not only of plastic materials, but also steel, glass and electrical materials. Therefore, it is important to predict an accurate amount of plastic material available for burning in order to gain an accurate value of the heat release rate. The amount of the plastic on a typical computer is assumed to be approximately 2 kg with the rest of the weight of the computer consisting of steel, glass and electrical substances. Only the plastic materials will be burned during the fire. The surface area for the pool fire after the melting of the plastic materials from the computer is assumed to be the area underneath the computer, which is about 0.3 m^2.

Figure 6.4.1 shows the heat release rate given off by the burning of the plastic materials of a typical computer as 0.2 MW. The duration of burning is approximately 7.2 minutes.

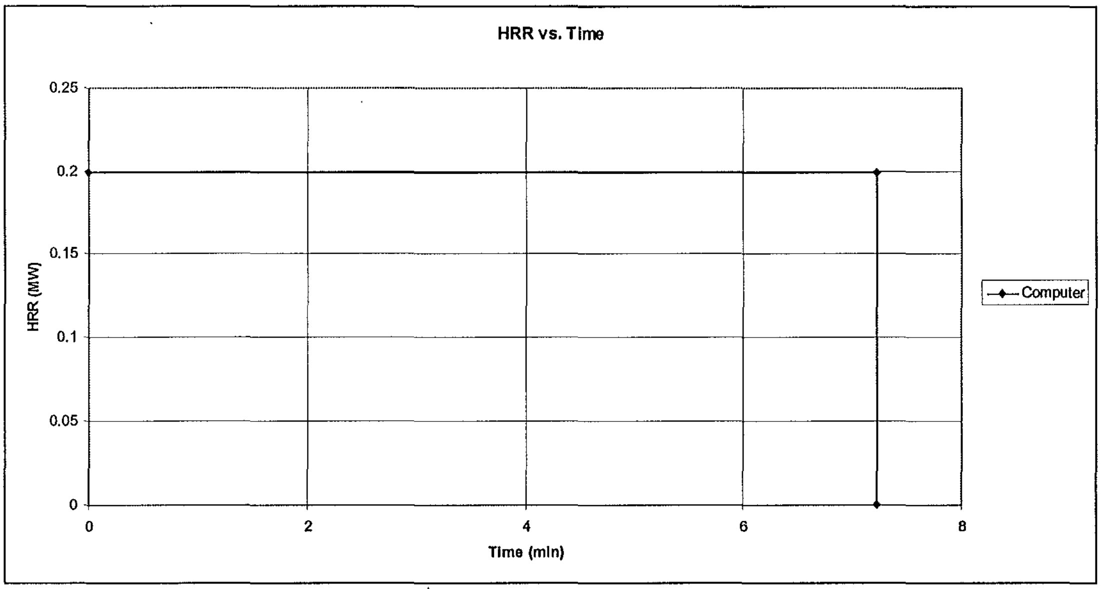


Figure 6.4.1: HRR vs. Time graph for a typical computer.

6.5 Cupboards

Cupboards are normally found in offices and residential rooms, and are considered to have a high fuel load. Besides their own wood materials, the contents of the cupboards, whether they are wood materials or plastic materials, also contribute to the fuel load.

6.5.1 Cupboard (I)

This type of cupboard is normally found in offices, especially university offices, and it is built in wood material. During the investigation of the effects of the surface area on the outcome of the heat release rate, the cupboard is consider to be in situation

(a) 100% full.

(b) Empty.

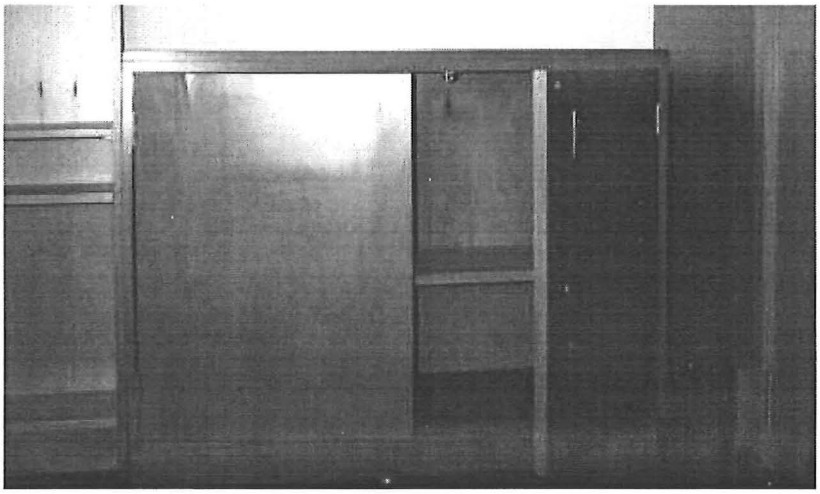


Figure 6.5.1.1: Cupboard (I).

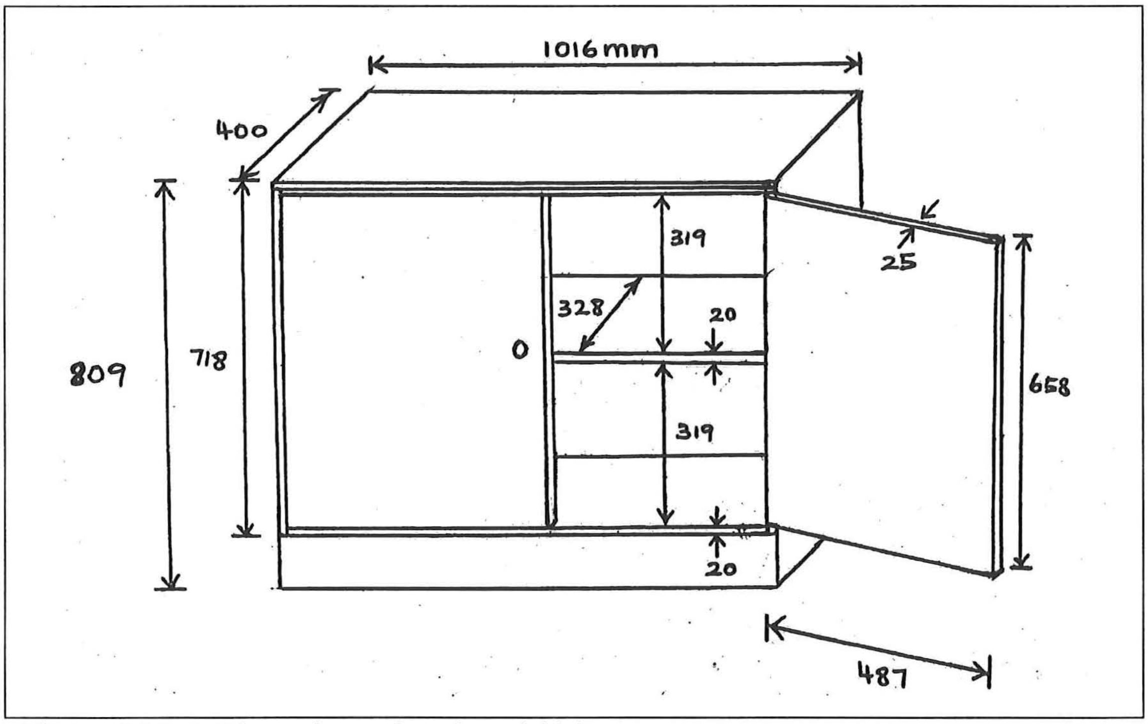


Figure 6.5.1.2: Dimensions of cupboard (I) in mm.

For situation (a), which is 100% full, the cupboard is considered to be a block. For the empty case in situation (b), the cupboard is divided into several thin pieces of wood which are freely exposed to fire.

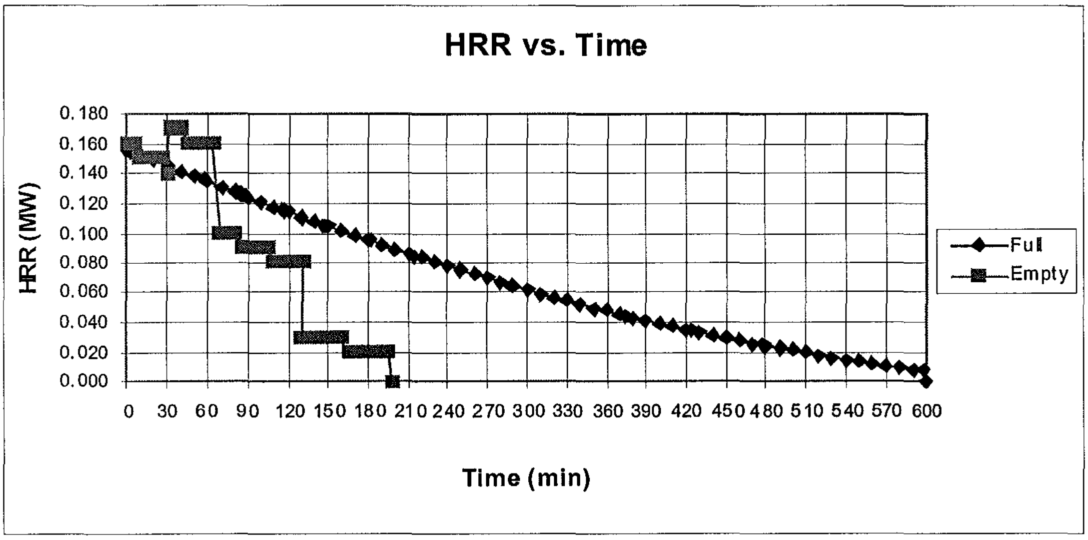


Figure 6.5.1.3: Comparison of HRR vs. Time graph for full and empty cupboard (I).

Figure 6.5.1.3 shows the different behaviour of the burning for a full cupboard and an empty cupboard. For a totally full cupboard, it is assumed that the cupboard is a completely full block without any space left. Therefore the outcome of the value of the heat release rate is the same as for a wooden cube block. However, the empty cupboard is divided into several parts. The thinner parts will be burned out first while the thicker will take more time to finish burning. At the beginning of the graph, which is approximately 30 minutes after the flashover, there is an increase in the value of the heat release rate after the drop. This is due to the exposure of the inner parts of the cupboard after the outer thinner parts of the cupboard have been burned through. Therefore, there is an increase in the value as more surface area is exposed. The duration of burning is far less than the full cupboard as the assessment for the empty cupboard is based on several thinner parts and not a solid block of fuel.

6.5.2 Small Cabinet

This small cabinet is normally used in storing books, clothes and other personal items. It is normally found in residential households. The cabinet itself is built with wood material. Due to its size, it is not considered to be a high fuel load during a fire. Again as with cupboard (I), the small cabinet is consider to be in situation

(a) 100% full of books and papers.

(b) Empty.

Figure 6.5.2.1: Small cabinet.

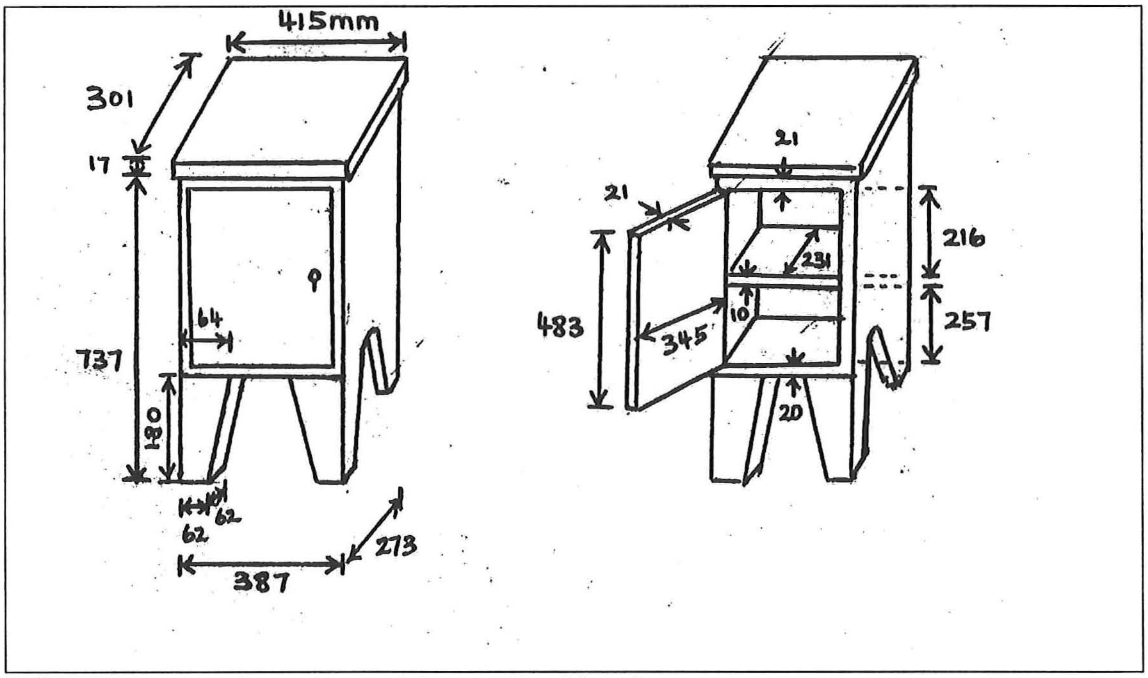


Figure 6.5.2.2: Dimensions of the small cabinet in mm.

For situation (a), which is 100% full, the small cabinet is considered to be a small block. For situation (b), which is empty, the cabinet is divided into several thin pieces of wood.

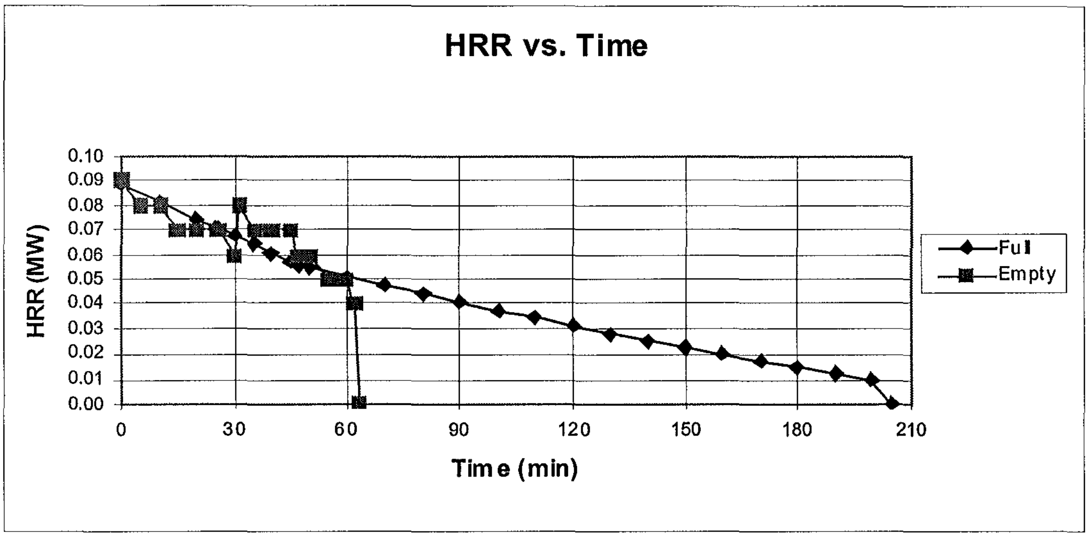


Figure 6.5.2.3: Comparison of HRR vs. Time graph for full and empty small cabinet.

Figure 6.5.2.3 shows the different behaviour of the burning for a full cabinet and an empty cabinet. For a totally full cabinet, the outcome of the value of the heat release rate is the same as for a wooden cube block. However, for the empty one, the small cabinet is divided into several parts. The thinner parts will be burned out earlier than the thicker parts. At the beginning of the graph, which is about 31 minutes after the flashover, there is an increase in the value of the heat release rate after the drop. This is due to the exposure of the inner parts of the cabinet after the outer thinner parts of the cabinet have been burned away. Therefore, there is an increase in the value as more surface area is exposed to the fire. The duration of burning is far less than the small, full cabinet.

6.6 Desks

Desks are made of wood material and are one of the major fuel loads in offices and flats. It is normally assumed the desk is full of books and papers, which has the same burning period as wood.

6.6.1 Desk (I)

This type of desk is found in flats, with its back placed close to the wall, which prevents that surface from being exposed to fire. During the prediction of the value of the heat release rate given off by the burning of desk (I), it is assumed the desk is full of books and papers without any spaces left.

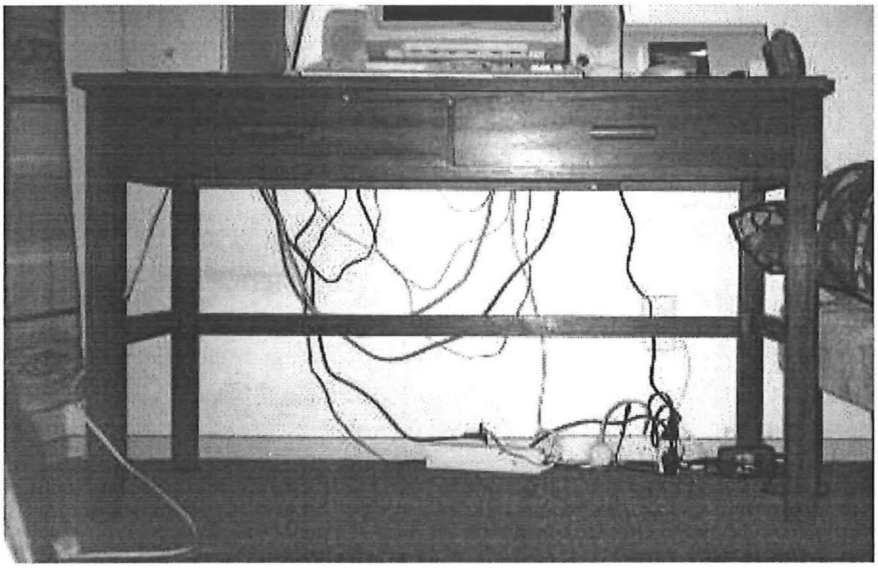


Figure 6.6.1.1: Desk (I).

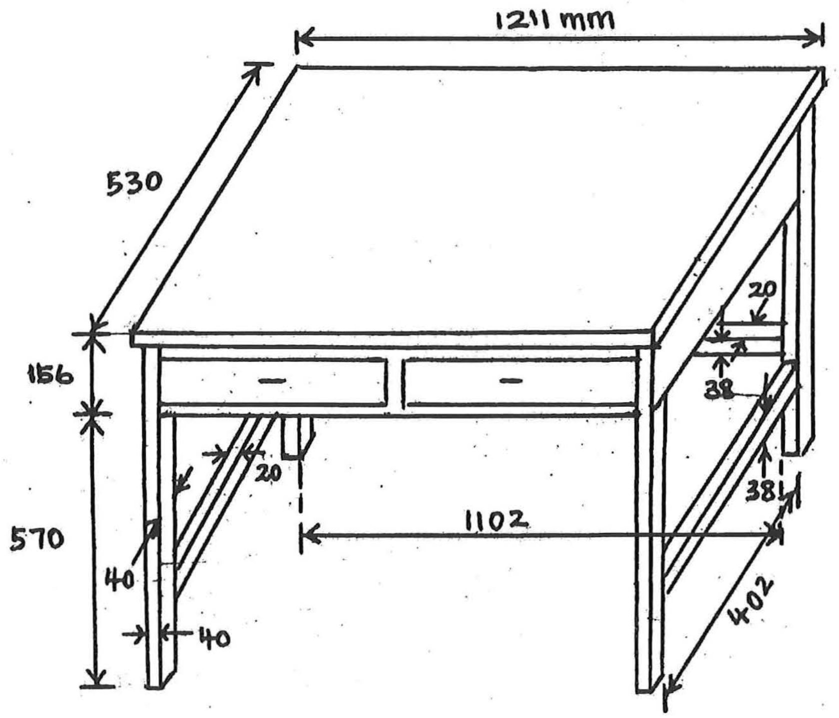


Figure 6.6.1.2: Dimensions of desk (I) in mm.

The main part of the desk and its two drawers, assumed to be full, is considered to be a block. Other thinner parts include the desk's legs.

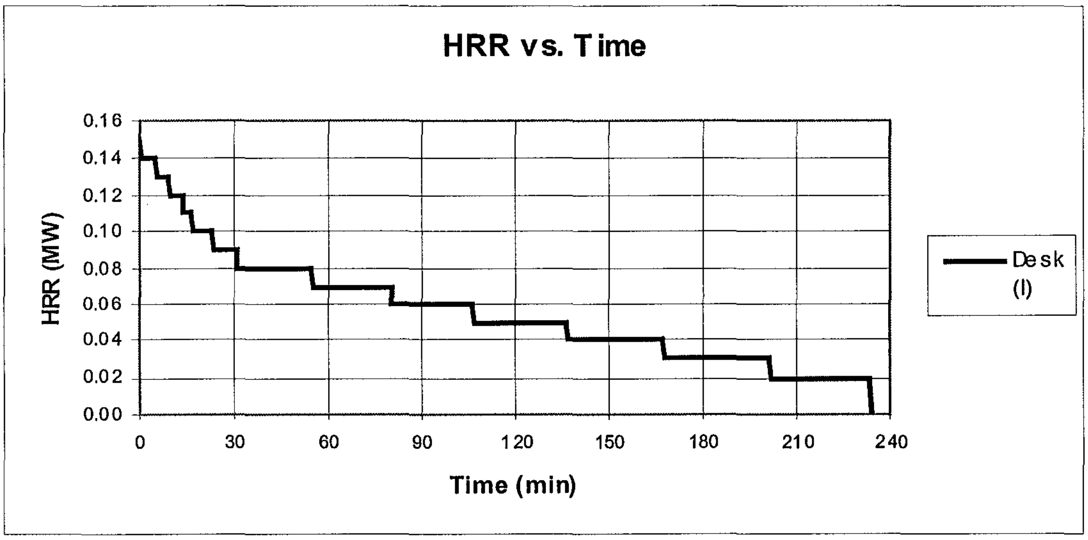


Figure 6.6.1.3: HRR vs. Time graph for desk (I).

The desk took about 230 minutes to complete the burning because of the thickness of its thickest part, which in this case is the main table surface with two drawers full of books. The maximum value of heat release rate is approximately 0.15 MW. One can see clearly from Figure 6.6.1.3 that each drop represents the complete burning of the thinner parts of the desk, mainly the legs. The thicker the parts of the desk, the longer it took to complete the burning.

6.6.2 Desk (II)

Desk (II) is normally found in offices and flats. It has two drawers at its side as shown in Figure 6.6.2.1. Again, it is assumed to be full.

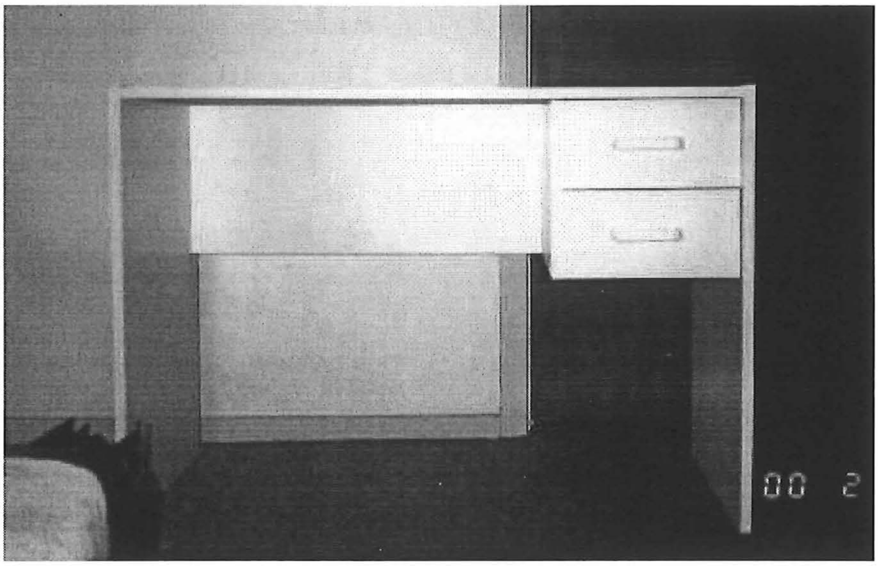


Figure 6.6.2.1: Desk (II).

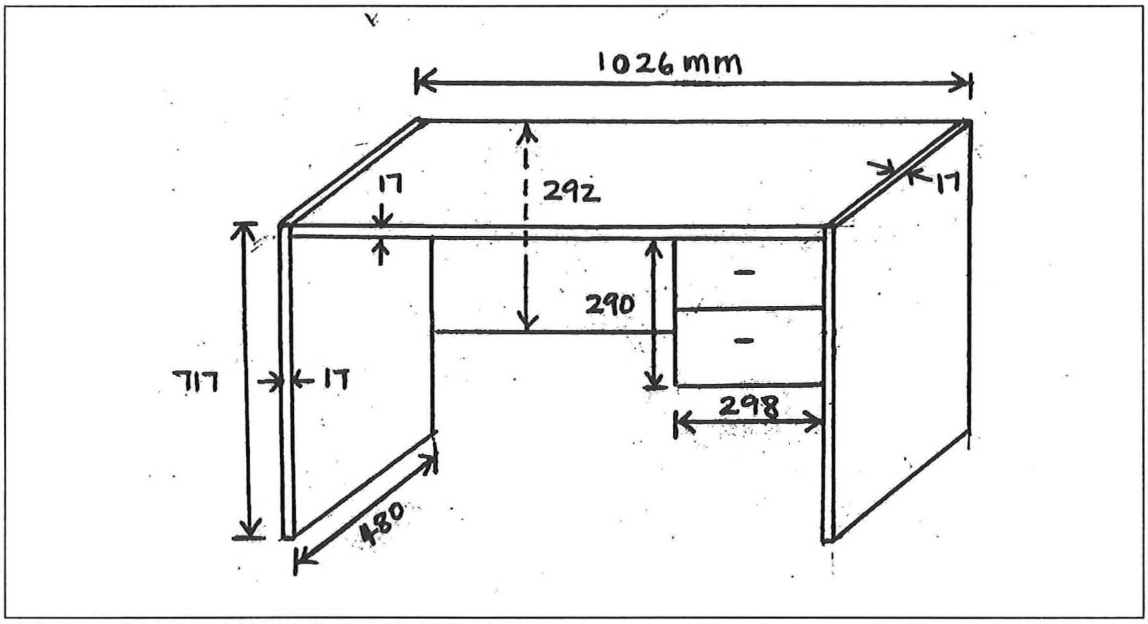


Figure 6.6.2.2: Dimensions of desk (II) in mm.

The desk is divided into several pieces of thin parts. Although the drawers are assumed to be full, there are normally still some spaces available. Therefore, a smaller block is assumed as the contents of each drawer.

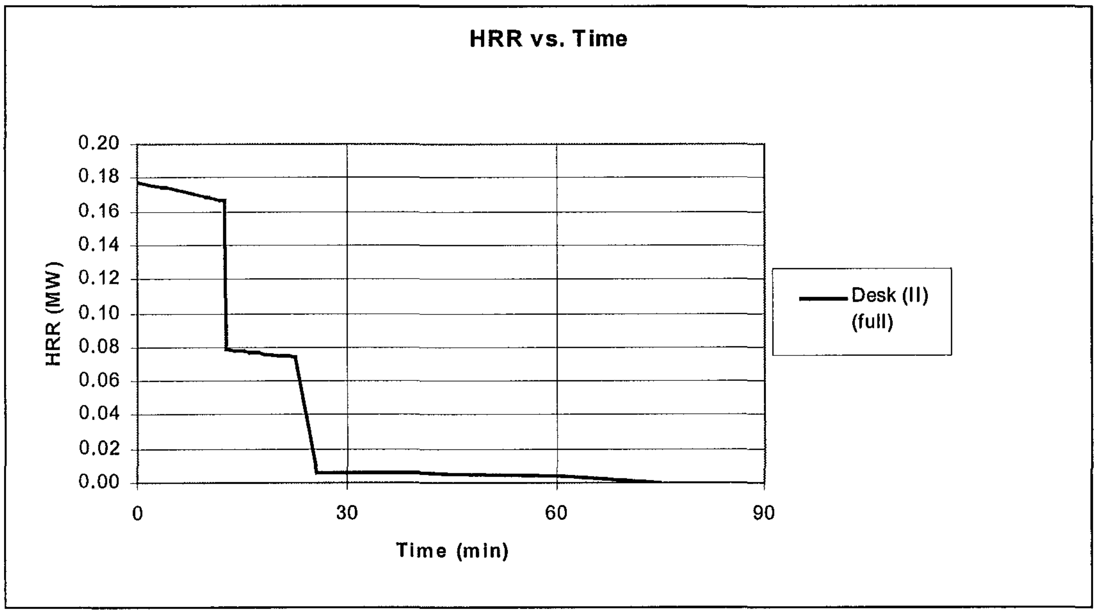


Figure 6.6.2.3: HRR vs. Time graph for desk (II).

The desk took about 75 minutes to complete the burning, and the time is dependent on the thickest part of the desk, which in this case was the contents of the drawers. This figure can change according to the amount of the drawers' contents. However, each drop in the value of the heat release rate in Figure 6.6.2.3 represents the complete burning of each part of the desk with the thinner parts gone first.

6.6.3 Desk (III)

Desk (III) can easily be found in postgraduate offices in the university. Normally, it is placed close to the wall with its back protected from exposure to the fire. Again as desk (II), it has two drawers but both are deeper.

Figure 6.6.3.1: Desk (III).

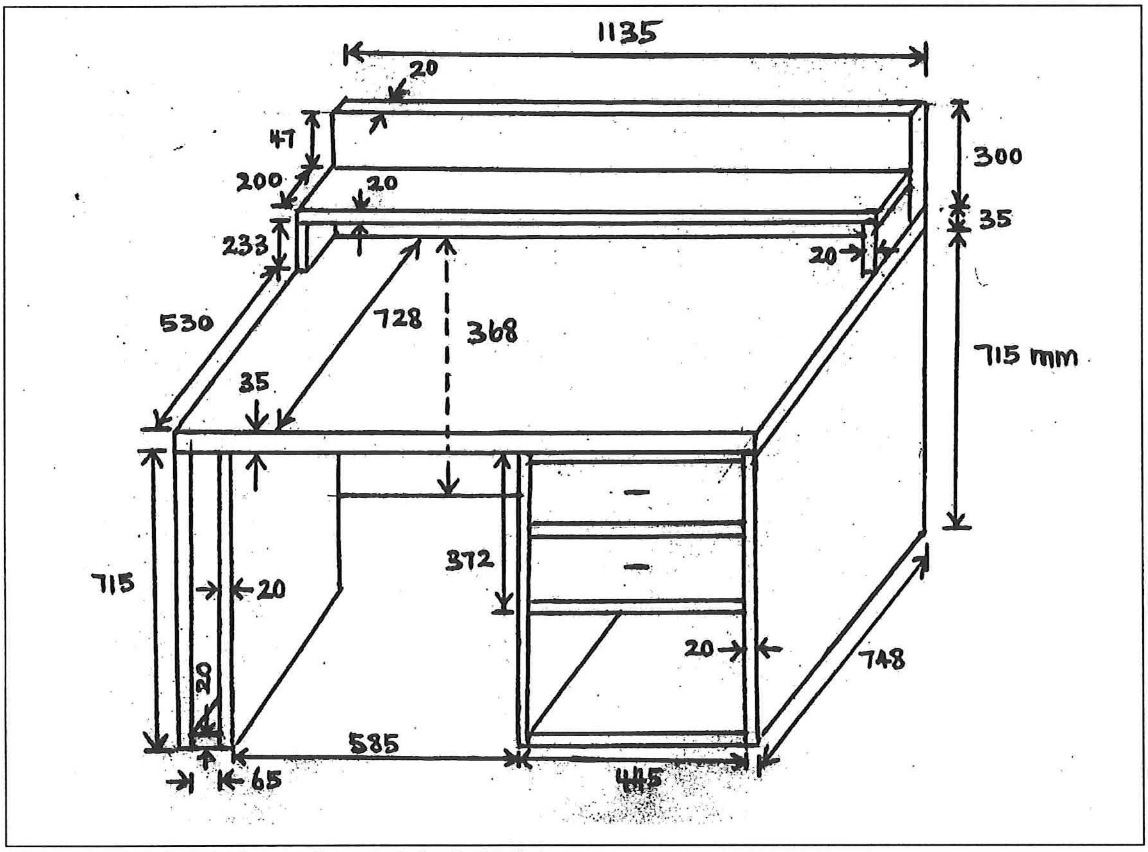


Figure 6.6.3.2: Dimensions of desk (III) in mm.

Again as before, desk (III) is divided into several pieces of thin parts. The drawers are assumed to be full but not entirely filled up with books and papers. There are still some spaces available inside the drawers, as in a real situation. Therefore, the content of the drawers is assumed to be a smaller block than in the case where no spaces are available.

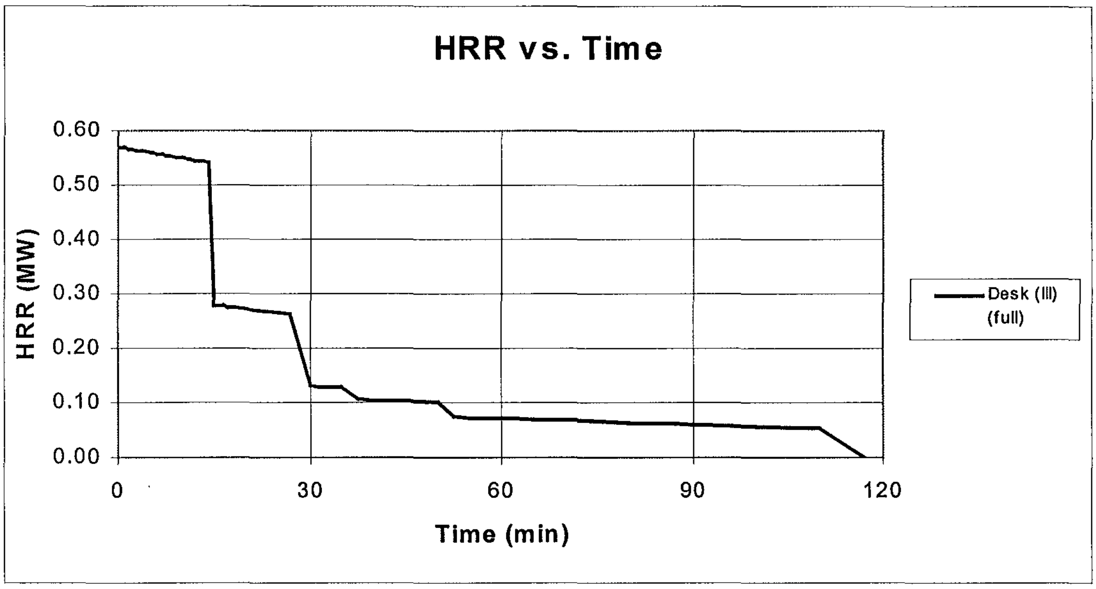


Figure 6.6.3.3: HRR vs. Time graph for desk (III).

The maximum heat release rate produced by desk (III) with a specified amount of content in the drawers is approximately 0.58 MW. The thinner part will be burned away first at the beginning of the burning period leaving behind the thicker parts. The thickest part of the desk is the content inside the drawers, and it took about 120 minutes to complete the duration of burning.

6.7 Steel Filing Cabinet

A steel filing cabinet itself is not considered to be a high fuel load during a fire, but the contents inside it are considered to be contributing to the total amount of fuel load available. Section 3.1.1 stated that combustible materials, such as files and papers, stored inside metal furniture, have been found to be only fractionally involved in fire, and most of them are left in good condition (Ingberg, 1928). However, to be able to predict the value of the heat release rate of the contents stored inside a steel filing cabinet based on the exposed surface area, it is assumed that the contents will be involved in the fire during the post-flashover fire due to the radiation and will continue to burn until completion. Figure 6.7.1 shows a typical type of filing cabinet normally found in offices.

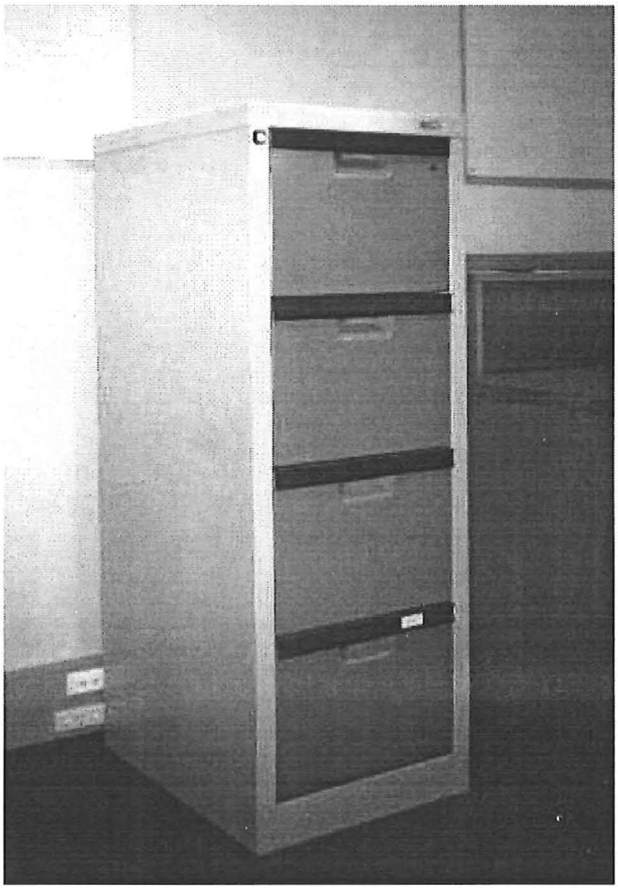


Figure 6.7.1: Typical steel filing cabinet.

The content inside each drawer is assumed to be a block, and the exposure to the fire depends on the amount of the content. In other words, the exposure to the fire depends on whether the contents are loosely packed or closely packed. If the contents are loosely packed, there will be more surface areas exposed to fire than in a closely packed situation. The contents are assumed to be blocks.

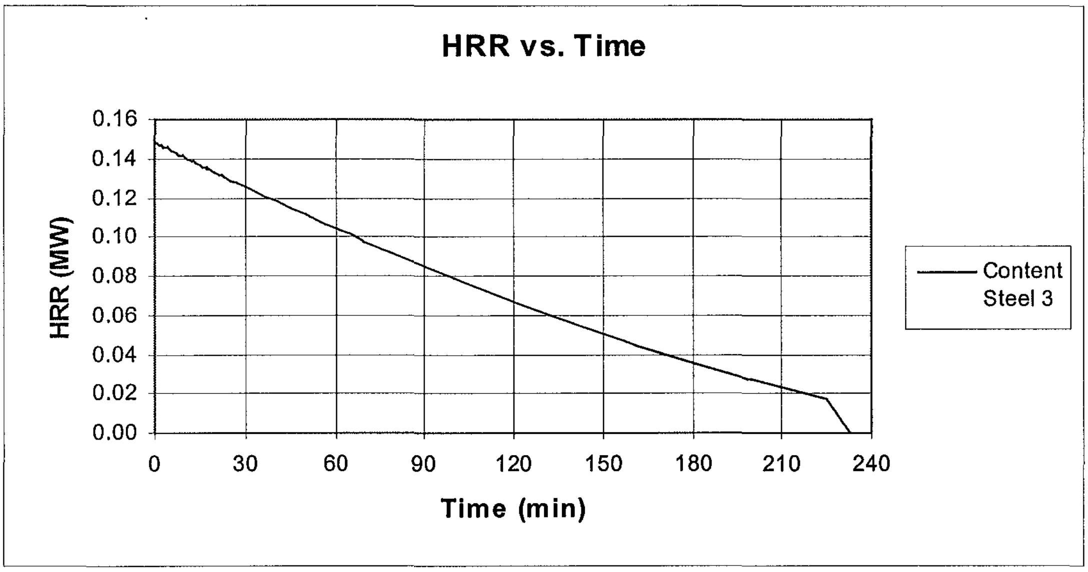


Figure 6.7.2: HRR vs. Time graph for the contents inside a typical steel cabinet.

The looser the contents are packed, the higher the value of the heat release rate as more and more surface of the contents is exposed to fire. The result shown in Figure 6.7.2 has a similar version of the outcome of heat release rate for a wooden cube block in Section 4.1.3. The contents will keep burning until all the fuel is gone.

6.8 Tables

Tables are another type of furniture, which can be seen almost everywhere. Tables can be made from all types of material. Some of them are made of wood, while others can be made of a combination of wood, steel or glass. However, only the wood materials are considered to be involved in fire as steel and glass materials do not have such a high fuel load during a fire. The value of heat release rate depends on the amount of the wood surface exposed to fire, and the duration of burning is dependent on the thickness of the wood material.

6.8.1 Table (I)

This type of table is normally found in offices. It is built from the combination of wood and steel. The main surface of the table consists of wood material, while the legs are made of steel. Therefore, only the surface of the table is considered here.

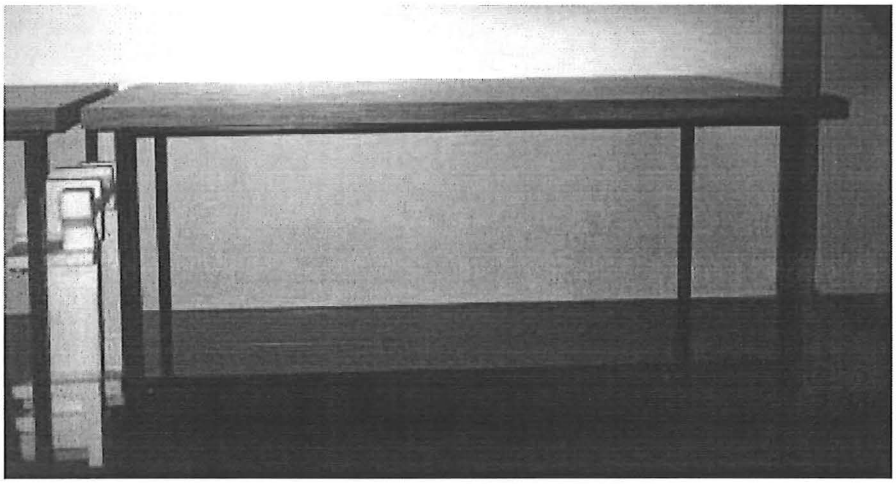


Figure 6.8.1.1: Table (I).

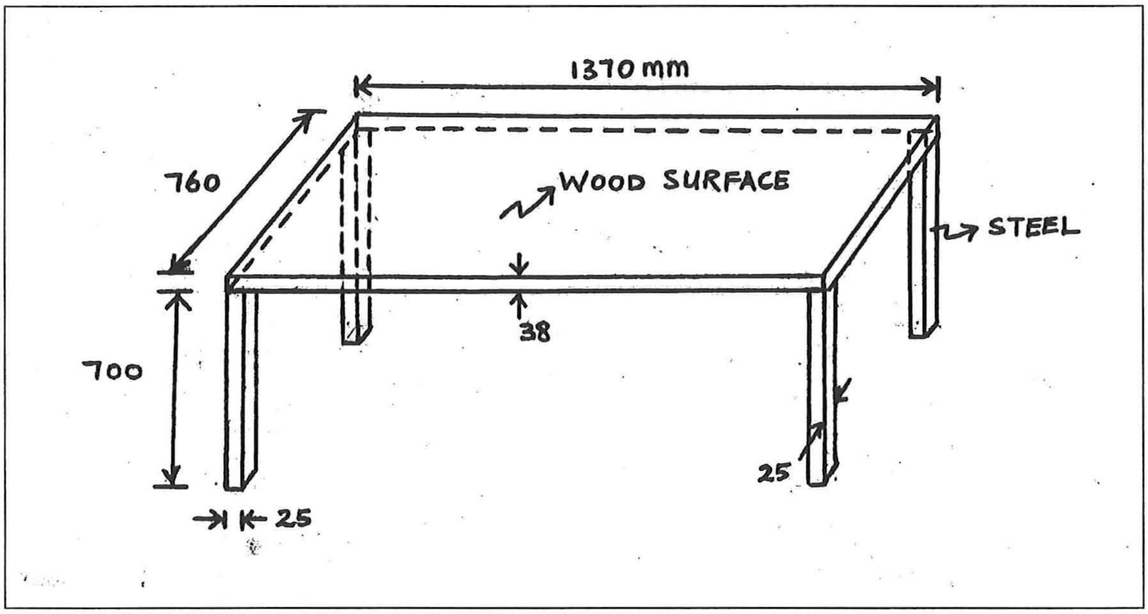


Figure 6.8.1.2: Dimensions of table (I) in mm.

As only the main surface of the table, which is built with wood material, is a concern here, the part is considered to be a thin rectangular slab.

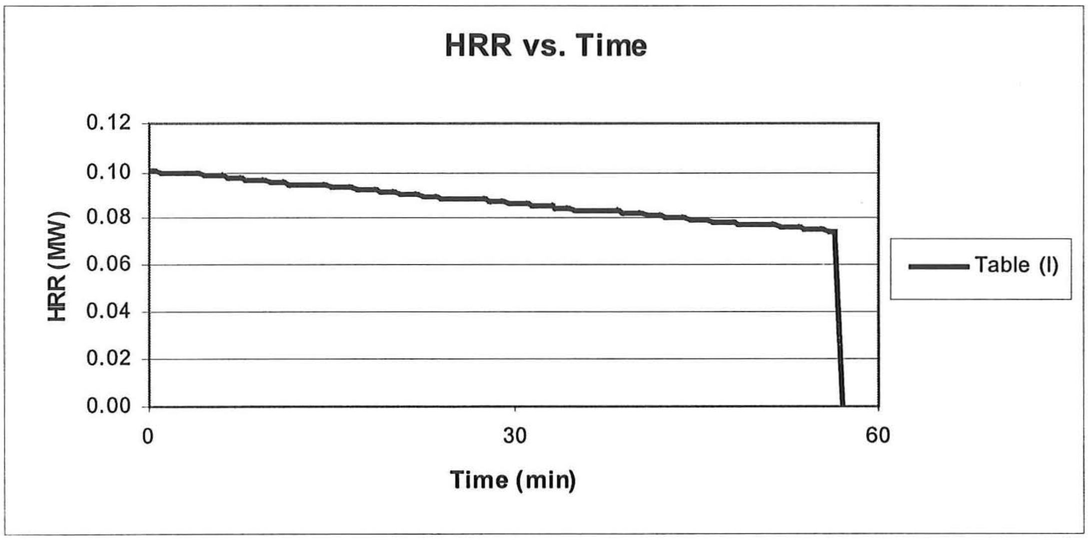


Figure 6.8.1.3: HRR vs. Time graph for table (I).

From Figure 6.8.1.3, it can be seen that the table burned more like in a stick situation than a cube block situation due to its extremely small thickness. The duration of burning was only about 55 minutes.

6.8.2 Table (II)

Unlike table (I), table (II) is built entirely with wood material.

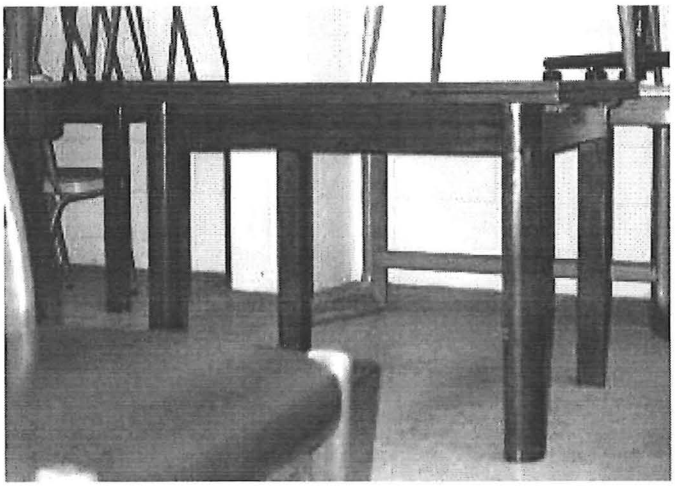


Figure 6.8.2.1: Table (II).

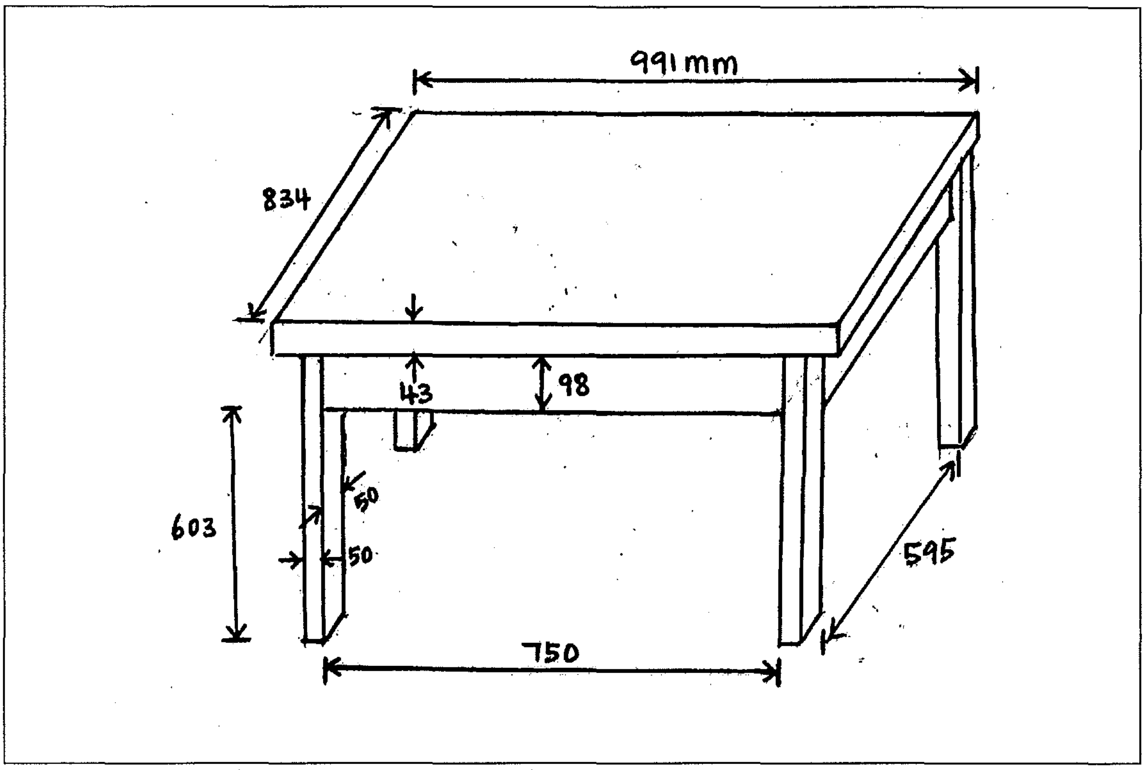


Figure 6.8.2.2: Dimensions of table (II) in mm.

The table is divided into several parts according to their thickness.

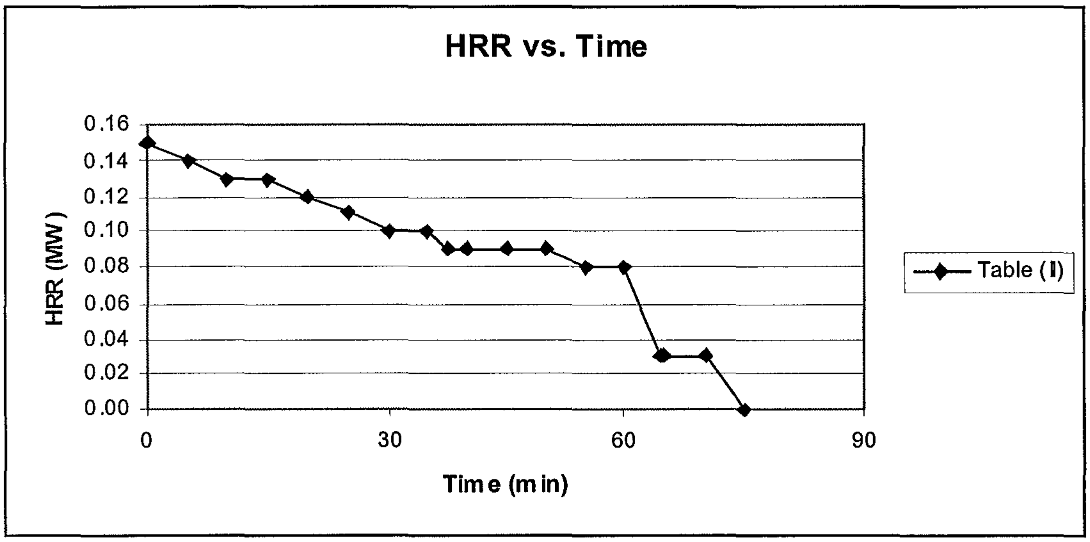


Figure 6.8.2.3: HRR vs. Time graph for table (II).

From Figure 6.8.2.3, it can be seen that there are many of drops in the value of the heat release rate. This indicates the completion burning of each part with the thinnest part burned away first, leaving behind the thicker parts. It took about 75 minutes to complete the burning of the thickest part of the table.

6.9 Upholstered Sofa

Upholstered sofas are normally built with polyurethane fabric and foam on a wooden frame. It is assumed that during the post-flashover fire, the solid upholstered material will melt and burn in a pool fire, leaving behind the wooden frame. The wooden frame is considered to be uninvolved in the fire by assuming the fire will go out as soon as the upholstered materials are gone, leaving only the wooden frame.

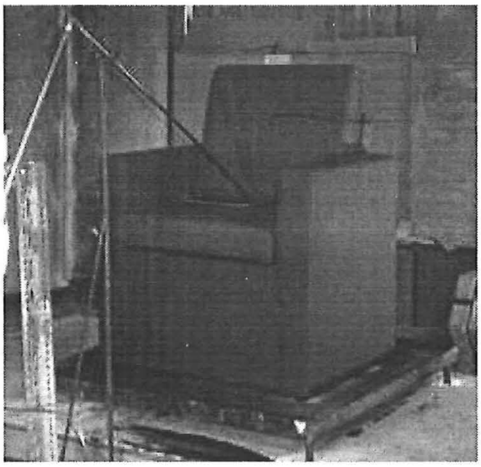


Figure 6.9.1: Typical upholstered sofa.

Figure 6.9.2 shows the effects of the pool area on the outcome of the heat release rate by considering the pool fire is in steady state. It is assumed that the fuel in the pool will be consistent during the cycle of the burning, and gone when the duration of the burning is reached, which in this case is about 9 minutes (550 seconds).

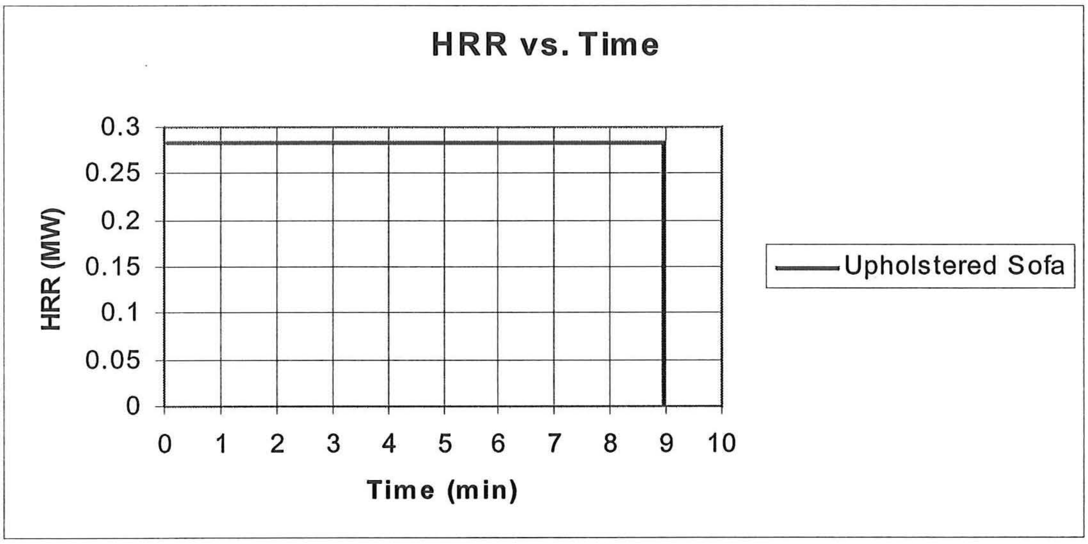


Figure 6.9.2: HRR vs. Time graph for a typical upholstered sofa.

6.10 Wooden Chairs

6.10.1 Stool

Figure 6.10.1.1 shows a typical type of stool. This stool is normally considered to be an extremely small fire load during a fire

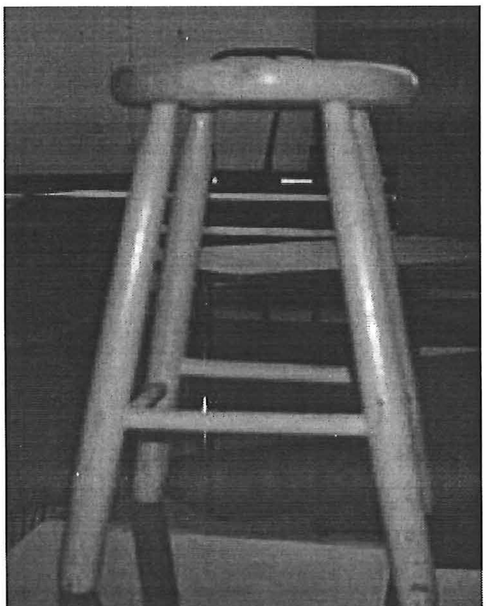


Figure 6.10.1.1: Stool.

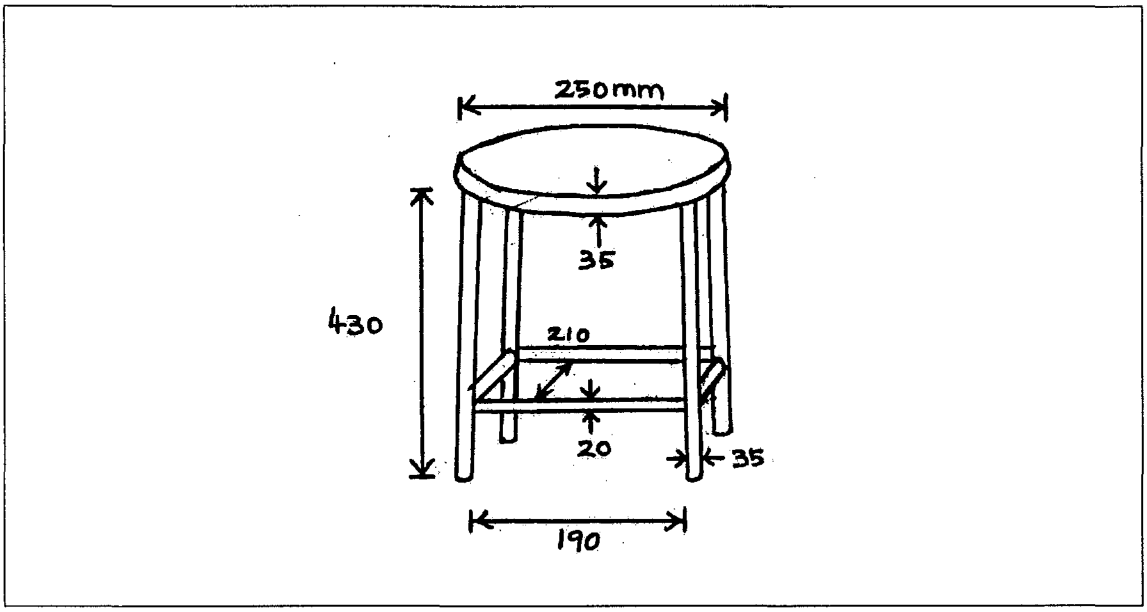


Figure 6.10.1.2: Dimensions of the stool in mm.

All the parts of the stool are considered to burn like a sphere due to the stool's shape. The duration of burning is dependent on the thickest part of the stool.

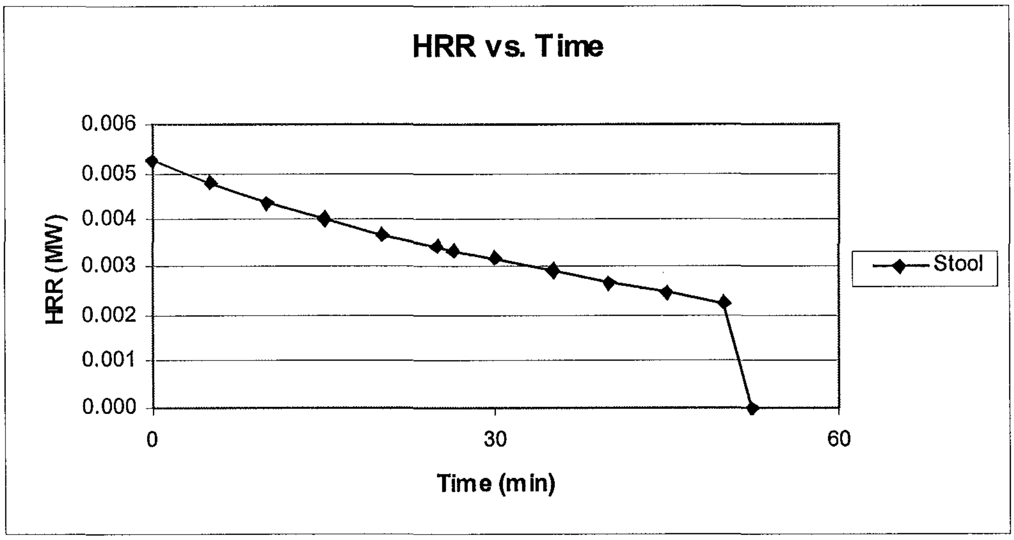


Figure 6.10.1.3: HRR vs. Time graph for stool.

Figure 6.10.1.3 shows the stool is going to behave as a sphere until all its parts exposed to the fire are gone.

6.10.2 Chair (I)

Chair (I) is built entirely with wood material. During the prediction of the value of the heat release rate, it is divided into several parts in order to simplify the modelling. From Figure 6.10.2.3, it can be seen that there are lots of drops in the value of the heat release rate. These indicate the thinner parts of the chair will complete their duration of burning faster than the thicker parts.

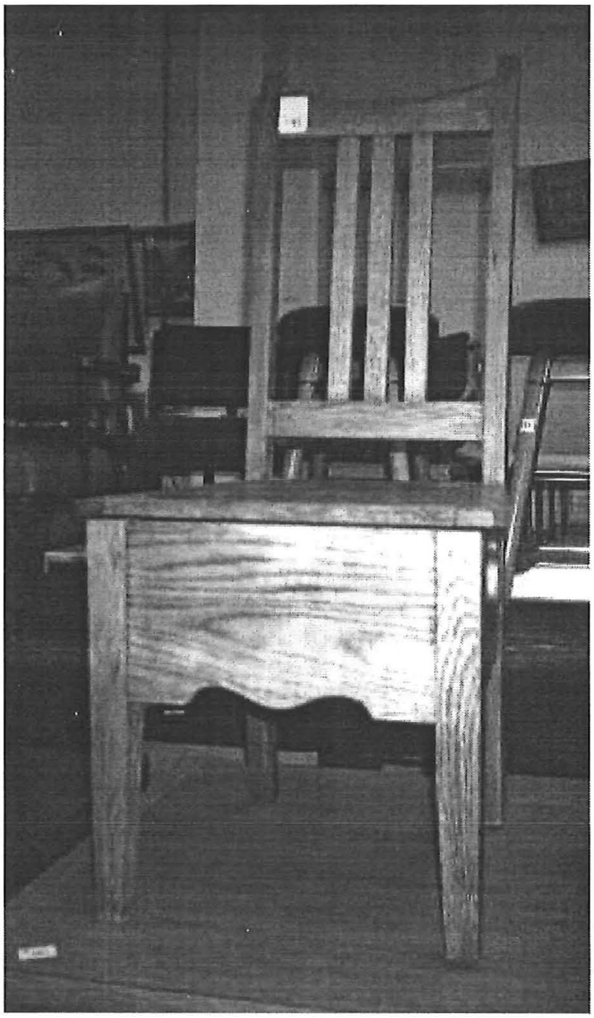


Figure 6.10.2.1: Chair (I).

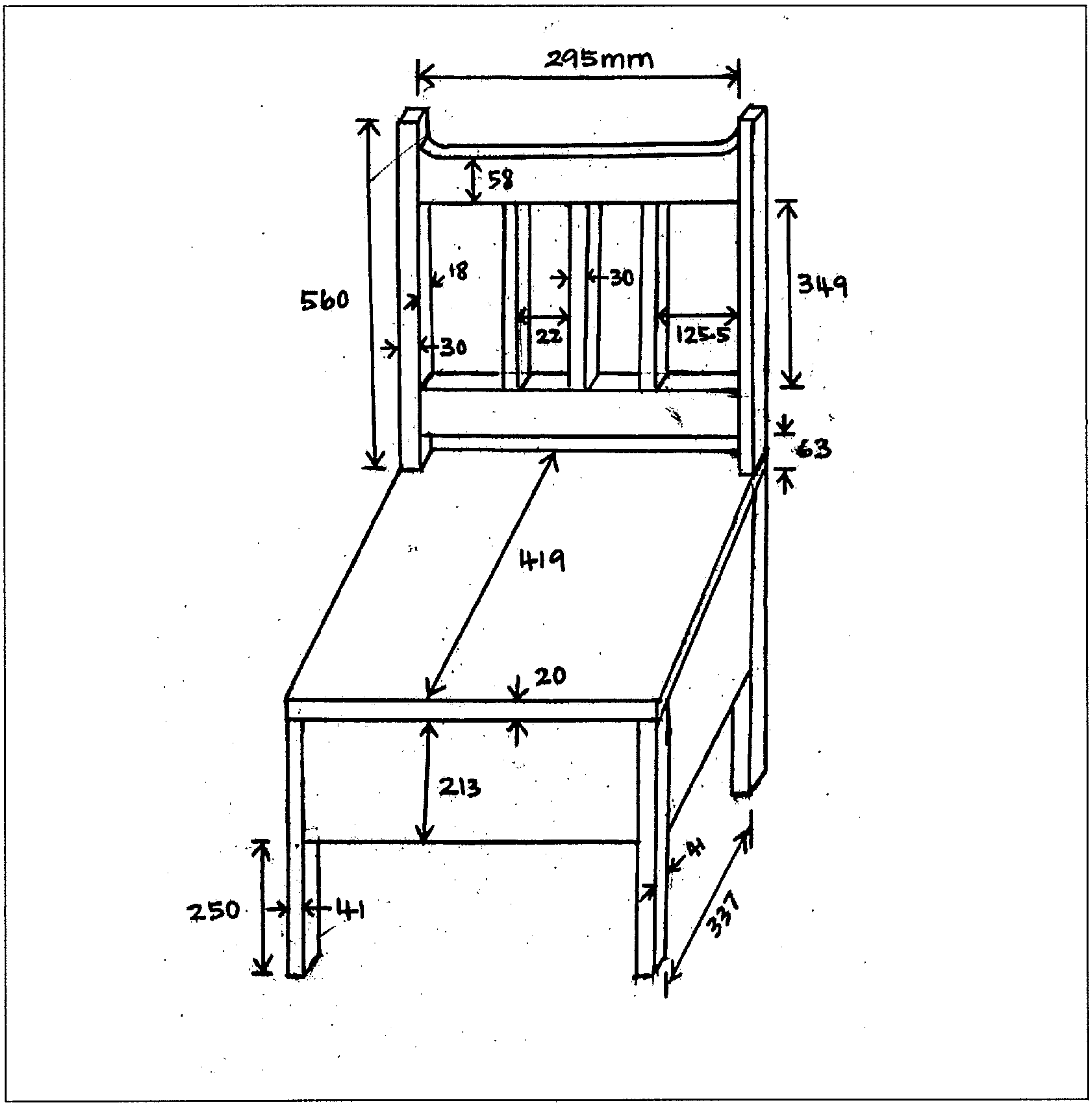


Figure 6.10.2.2: Dimensions of chair (I) in mm.

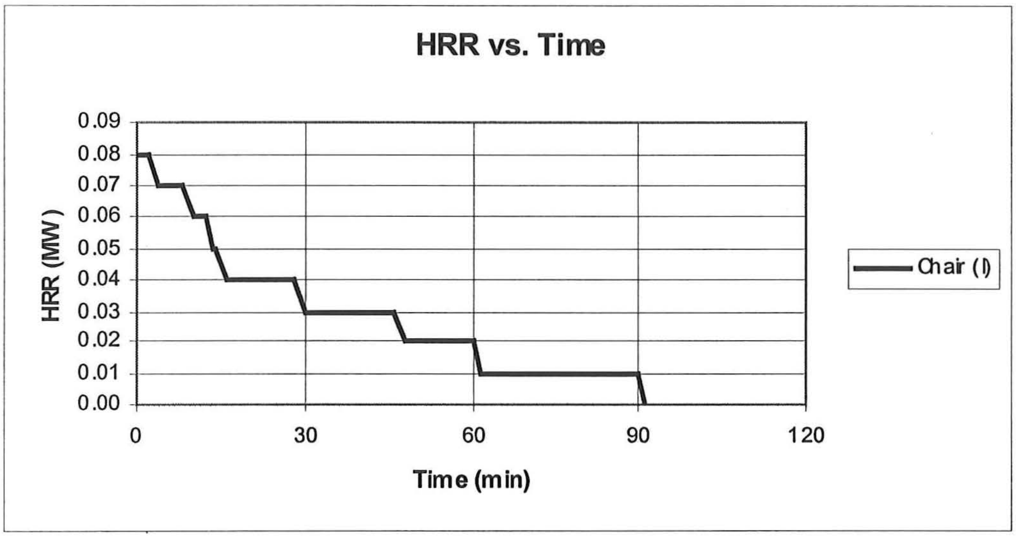


Figure 6.10.2.3: HRR vs. Time graph for chair (I).

6.10.3 Chair (II)

Chair (II) is another version of chair (I). As before the result shows a similar trend (with smoother curve), but it took less time to complete the whole burning as chair (II)'s thickest part is thinner than chair (I)'s thickest part.

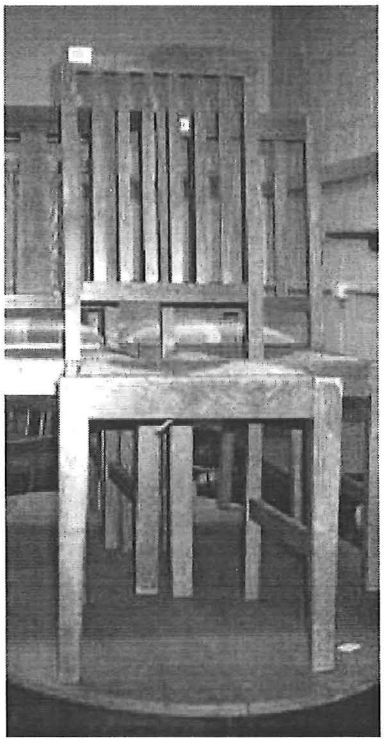


Figure 6.10.3.1: Chair (II).

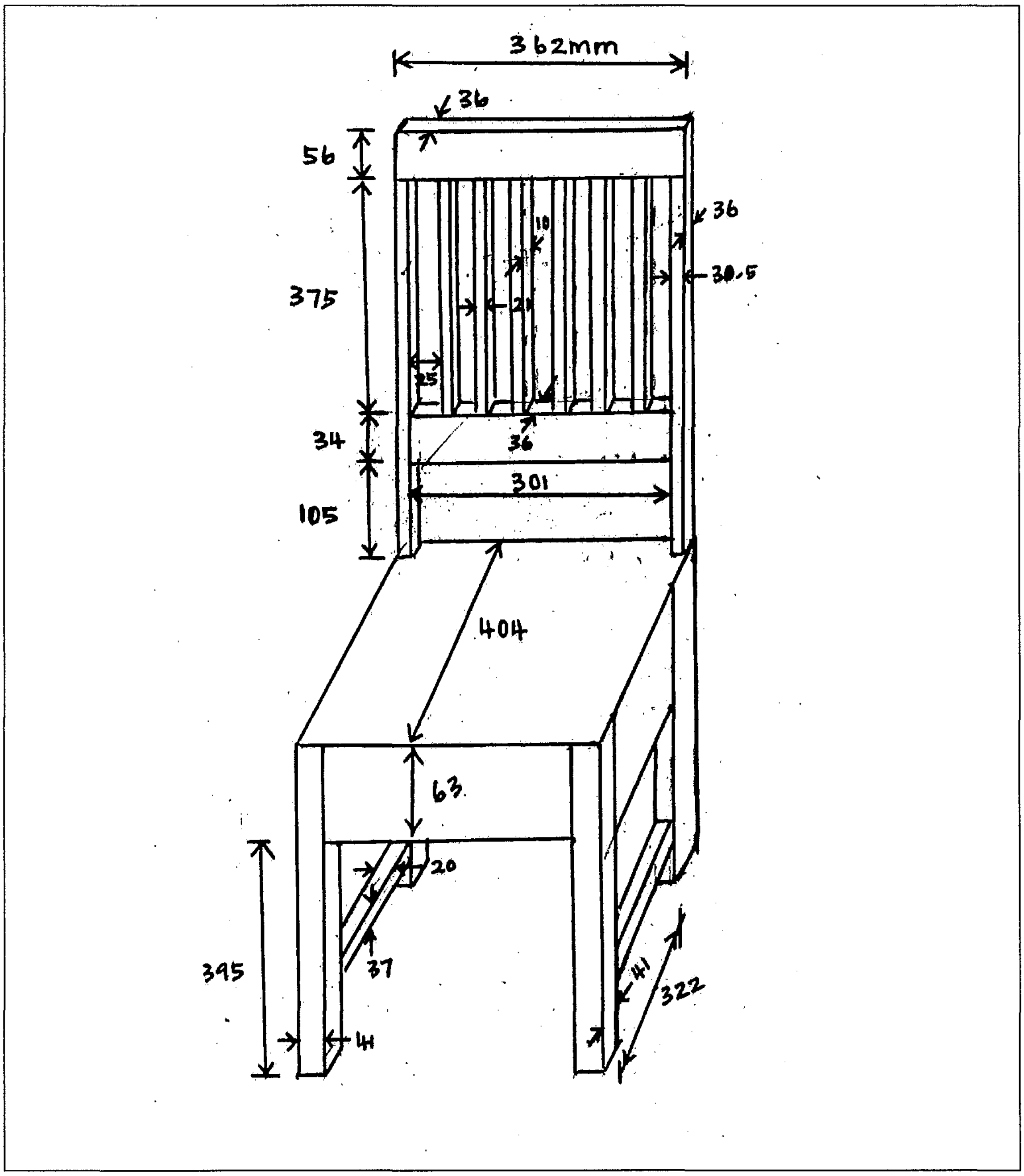


Figure 6.10.3.2: Dimensions of chair (II) in mm.

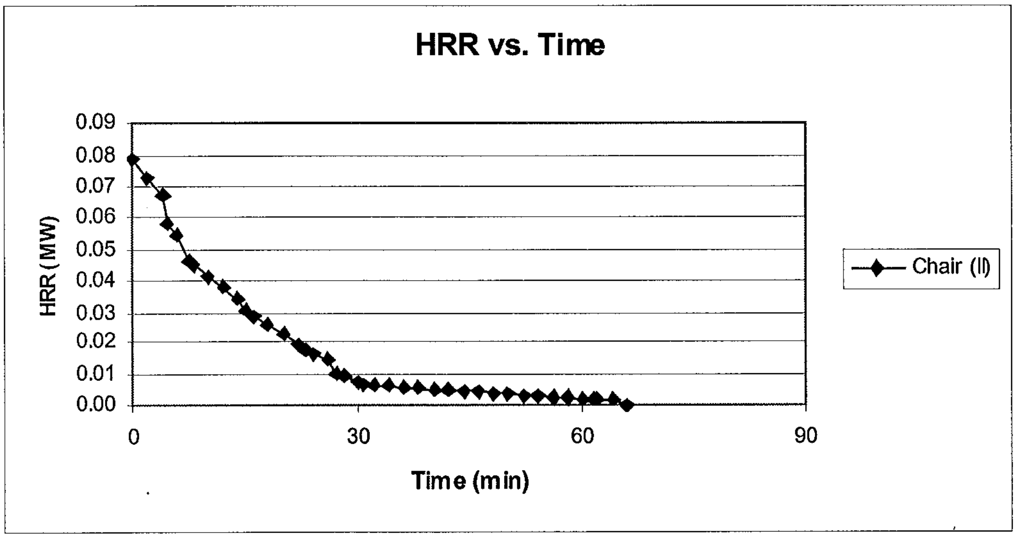


Figure 6.10.3.3: HRR vs. Time graph for chair (II).

7. FIELD SURVEY

Field surveys to estimate the surface area of the fire load in certain building occupancies were carried out to assess the possible heat release rate. Six samples of university rooms, four samples of postgraduate offices, one sample of a motel unit (kitchen and bedroom), and four samples of bedrooms in flats have been assessed.

7.1 Data Collection

All data was collected on a fire load data entry sheet as shown in Appendix B. Besides recording the designation of the fuel load, the fuel load is also divided into different type of materials such as wood, plastic, and glass to simplify the modelling later on.

The number of quantities of each type of fuel load is also recorded so that an accurate heat release rate present in the enclosed fire compartment can be predicted. The mass and the dimensions, which are the important variables needed, are measured. For fuels which are too large to measure, the volume of the object is measured and the mass is obtained by multiplying the volume with the density.

As the main purpose of the surveys is to predict the value of the heat release rate based on the exposed surface area of the fuel to the fire, the surface areas of the fuel that are exposed to the fire are also carefully assessed. This is done by indicating how many sides of the fuel's surface are exposed to fire.

In order to simplify the data collection during the field surveys, the fuel loads are divided into two main categories, which are:

a) Fixed fire load.
b) Moveable fire load.

7.2 Fixed Fire Loads

This category consisted of items such as floor coverings (carpets), built-in cupboards or bookshelves, door and frames, and window sills. Other fixed items such as skirting boards and wall switches are ignored due to the difficulties in assuming the exposed surface area to the fire in order to predict the heat release rate. On the other hand, these provide a small contribution to the value of the heat release rate.

7.3 Moveable Fire Loads

This category covered much more diverse items and included such things as furniture, computers, televisions, books and papers, pictures, telephone, rubbish bins and personal effects. This category involved all the items that can be easily taken out or put into the fire compartment. Every item is carefully measured and weighed to predict the possible results.

7.4 Ventilation

Besides the fuel loads, the ventilation openings present in the enclosed fire compartment are also taken into account during the field surveys. This is because, as mentioned in Chapter 5, during the post-flashover fire, the burning of the fuel loads is going to be limited by the amount of available air need to support the burning.

Therefore, the dimensions of the window size and shape, which are opened to the open air outside the building, are also carefully assessed. Although there is also a door available to the fire compartment, it is ignored as the door is opened to a corridor with limited ventilation inside the building. Furthermore, during the modelling, it is assumed that the door is closed and all the glass on the windows will be broken during the post-flashover fire.

8. RESULTS ANALYSIS, SUMMARY AND COMPARISON

As described in Chapter 5, the value of the heat release rate of the fuel inside the fire compartment is going to be higher than the ventilation limit. The surface area of fuel inside the fire compartment exceeds the available air supply which can support the burning.

Therefore, two options are proposed to explain the behaviour of the burning of the fuel load based on the surface area exposed to fire. These are:

a) Beyond the ventilation limit, assume that all fuel burns outside the windows or
b) Assume the amount of energy beyond the ventilation limit will be burned first inside the office (nearer to the windows) (E1), then the energy released by the burning fuel under the ventilation limit will take place (E2).

These options can be looked at in more details in the following results.

8.1 Postgraduate Offices

8.1.1 E306

The office has a dimension of 5.89 m x 2.82 m. It has one opening to the outside with the dimension of 1.47 m x 2.27 m, assuming the glass broke during the post-flashover fire. Although the office has a door with a dimension of 1 m x 2.2 m, it is not considered to be a source of ventilation as it opens to a corridor, which has limited air, inside the building. Besides that, the door is considered to be closed during the modelling.

The office contains all sorts of fuel load ranging from wood materials to plastic materials, which are assumed to be ignited all at once during a post-flashover fire. The exposed surface areas of each item are carefully assessed. Table 8.1.1.1 below shows the summary descriptions of each item.

Fire Load	Type	Quantity	Dimensions (m)	Mass (kg) (approx.)	Surface Area Exposed
Fixed					
Bookshelf (I) ~ 50% full	W	1	See Figure 6.2.1.2	20 ea	All faces except back
Bookshelf (I) ~ empty	W	1	See Figure 6.2.1.2	12 ea	All faces except back
Carpet	P	1	5.89 x 2.82	28 ea	Exposed from upper face
Door + frame	W	1	0.91 x 2.225 x 0.02	20 ea	Exposed from inside the compartment
Window sill	W	1	2.27 x 0.2 x 0.035	8 ea	Front and upper faces exposed
Notice board	W	4	0.9 x 0.6 x 0.018	5 ea	All faces except back
Moveable					
Table (I)	W +S	3	See Figure 6.8.1.2	20 ea	All faces except the part underneath the table
Telephone	P + S + E	1	0.165 x 0.225	1 ea	Exposed from upper and side faces
Plastic chair (I)	P	3	0.5 x 0.45	12 ea	Exposed from upper and side faces
Plastic chair (II)	P + S	4	0.41 x 0.22	7 ea	Exposed from upper and side faces
Blinds	P	1	2.27 x 1.47	3 ea	Exposed from upper and side faces
Computer	P + S + G + E	2	0.64 x 0.4	10 ea	Exposed from upper and side faces
Box of foams	P	2	0.39 x 0.45	1 ea	Exposed from upper and side faces
Desk (III) ~ full	W	3	See Figure 6.6.3.2	30 ea	All faces except back
Bookshelf (III) ~ 60% full	W	1	See Figure 6.2.3.2	50 ea	All faces except back
Steel cabinet (I)	S	1	0.49 x 0.71 x 0.645	20 ea	N/A*
Contents of steel cabinet (I) ~ 75%	W	1	0.4 x 0.35 x 0.48	5 ea	All faces except the part underneath
Steel cabinet (IV)	S	1	0.46 x 1.32 x 0.64	25 ea	N/A*
Contents of steel cabinet (IV) ~ 25%	W	3	0.4 x 0.3 x 0.05	3 ea	All faces except the part underneath
Bundle of books and papers	W	3	0.29 x 0.09 x 0.21	3 ea	All faces except the part underneath
Drawing board	W	3	0.405 x 0.605 x 0.015	3 ea	All faces except the part underneath
Rubbish bin	S	1	diameter = 0.3	1 ea	N/A*
Others plastic things	P	1	0.5 x 0.2	1 ea	Exposed from upper and side faces
Papers	W	2	0.3 x 0.21 x 0.03	1 ea	Exposed from upper and side faces
		4	0.3 x 0.21 x 0.005	~ 0.2 ea	Exposed from upper and side faces
		1	0.9 x 0.6 x 0.0001	~ 0.1 ea	Exposed from upper and side faces

** N/A ~ steel materials are considered to be low fuel load in fire. Thus, surfaces are not involved in the fire.*

W = Wood, P = Plastic, S = Steel, E = Electrical, G = Glass.

Table 8.1.1.1: Summary descriptions of each fuel load in office E306.

During the modelling for each item available inside office E306, besides the thinner portion of cellulosic materials, such as thin, loose paper sheets, it is found that almost all the non-cellulosic materials have a shorter burning period than the thicker portion of the cellulosic materials. In other words, thermoplastic materials will burn out before wood materials.

Figure 8.1.1.1 shows the layout of office E306.

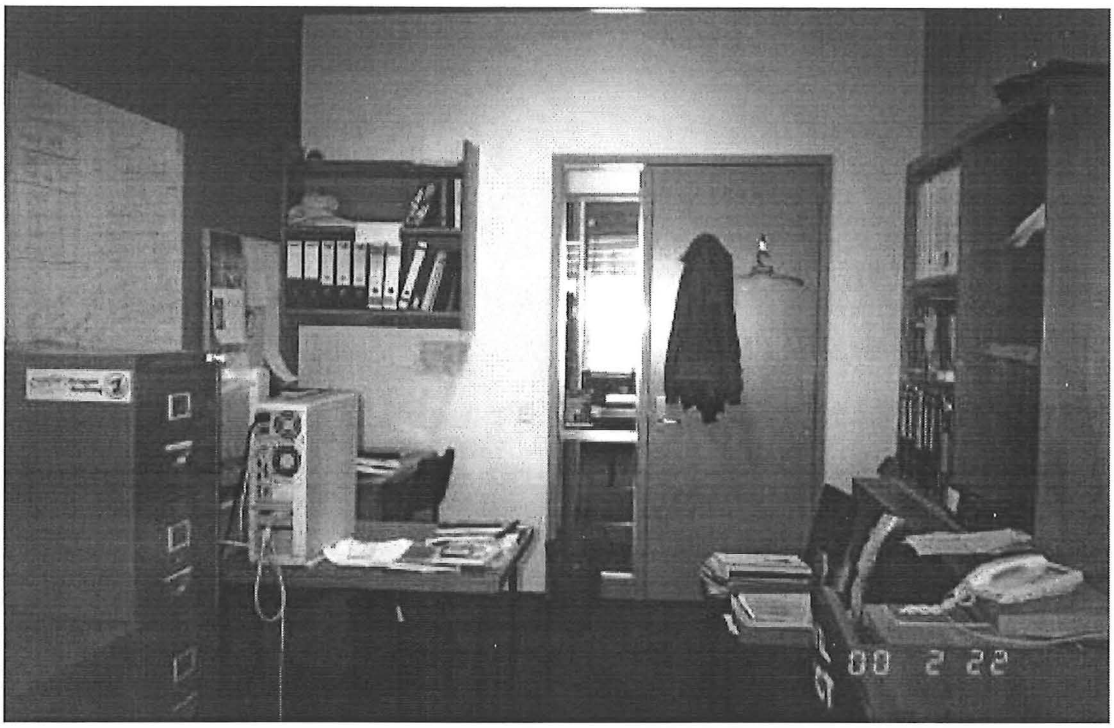


Figure 8.1.1.1: Layout of E306.

Figure 8.1.1.2 below shows the total amount of heat release rate available inside the office. The maximum value of the heat release rate is approximately 19 MW, based on the total exposed surface area of the fuel loads during a post-flashover fire. However, the ventilation limit is only about 6 MW, based on the available ventilation to the office. From the figure, it also can be seen that there is a large drop in the value of the heat release rate at the beginning of the burning duration. This is due to the complete burning of the thinner portions of the fuel loads. These include the carpet, the blind and all the thin, loose paper sheets lying inside the office. Besides that, the high value of the heat release rate at flashover is due to the large amount of total surface area exposed, especially the surface area contributed by the carpet. After the large drop, the value of heat release rate decreases more steadily, as the burning of the thicker portions of the fire loads takes place. The duration of burning is based on the thickest part of the item inside the office, which in this situation is the built-in bookshelf 50% full of books and papers.

The fire load density for this office is approximately 900 MJ/m^2. Although this value shows that the amount of the fuel load inside the office is quite high, one would expect to see a higher portion of heat release curve predicted beyond the ventilation limit. This is due to the quantities of the burning fuel exceeding the available ventilation which is needed to support the burning.

However, as seen in Figure 8.1.1.2, the result obtained is not as expected. This is because the outcome of the value of the heat release rate is based on the total amount of the exposed surface areas of the fuel loads to the fire, and not the total amount of the fuel loads (in kg) stored inside the office, as considered in previous surveys. Consequently, this means that the lesser the surface area exposed to the fire, the lower the value of the heat release rate. As most of the furniture inside the office is full (ie. bookshelf full of books), simple shape of the fuel is adopted in predicting the surface area exposed for each complicated item. This reduced the possibility of more surfaces being exposed to the fire, which in turn reduced the value of the heat release rate. This explanation can be supported by the data presented for single items in Chapter 6 (ie. see section 6.2).

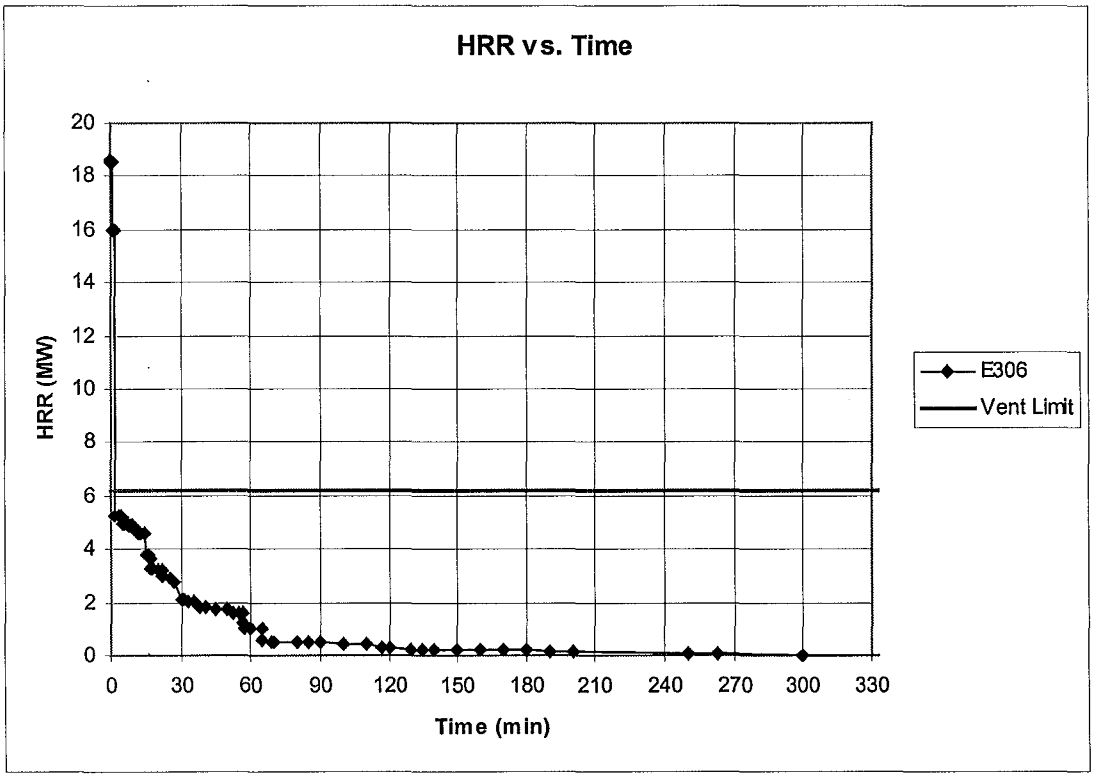


Figure 8.1.1.2: HRR vs. Time graph for fuel load inside office E306.

As mentioned earlier, there are two options in describing the outcome of Figure 8.1.1.2 above. There is option (a), which suggested that the fuel is burning outside the building, at which the heat release rate curve is beyond the ventilation limit. However, from the figure above, it can be seen that most of the amount of surface controlled heat release rate that are beyond the ventilation limit belongs to the thinner portion of the fuel. Therefore, it is unlikely to consider that these fuels are being burned outside the office in the open air.

Therefore, option (b) is considered. Figure 8.1.1.3 shows the concept described for option (b) earlier. The amount of heat release rate beyond the ventilation limit (E1) shifts downward, under the ventilation limit, and the original amount energy under the ventilation limit (E2) shifts to the right side of E1.

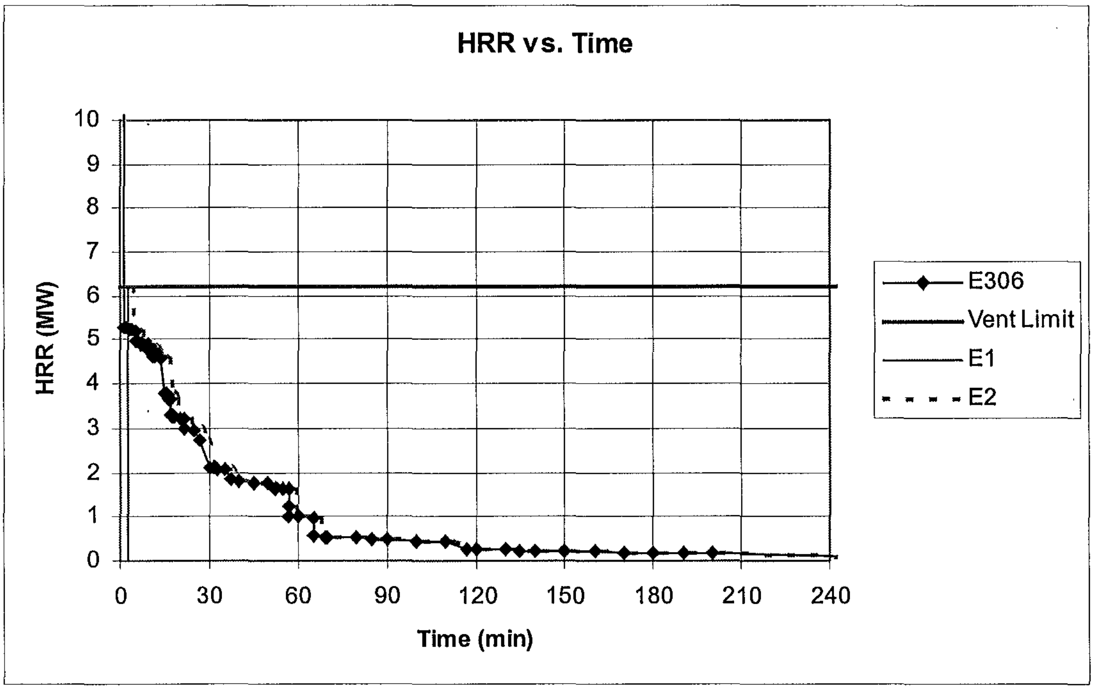


Figure 8.1.1.3:HRR vs. Time graph showing the shifting of E1 and E2 under the ventilation limit for office E306.

By shifting and dividing the original curve into E1 and E2, the heat release rate curve will shift by only three minutes. This is only a small difference. Figure 8.1.1.3 indicates that E1, which is nearer to the window, will be burned first before the burning of the further fuel loads takes place.

8.1.2 E312

This office is larger than the office before. It has a dimension of 6.07 m x 5.965 m. It has a small opening to the outside with the dimension of 0.65 m x 2.22 m, assuming the glass broke during the post-flashover fire. Although it has a door with a dimension of 1 m x 2.2 m, it is not considered to be a source of ventilation as it opens to a corridor, which has limited air, inside the building. Besides that, the door is considered to be closed during the modelling.

The office contains all sorts of fuel load ranging from wood materials to plastic materials, which are assumed to be ignited all at once during a post-flashover fire. The exposed surface areas of each item are carefully assessed. Table 8.1.2.1 below shows the summary descriptions of each item.

Fire Load	Type	Quantity	Dimensions (m)	Mass (kg) (approx.)	Surface Area Exposed
Fixed					
Bookshelf (I) ~ 25% full	W	1	See Figure 6.2.1.2	17 ea	All faces except back
Bookshelf (I) ~ 12.5% full	W	3	See Figure 6.2.1.2	15 ea	All faces except back
Bookshelf (I) ~ empty	W	2	See Figure 6.2.1.2	12 ea	All faces except back
Carpet	P	1	6.07 x 5.965	60 ea	Exposed from upper face
Door + frame	W	1	0.91 x 2.225 x 0.02	20 ea	Exposed from inside the compartment
Window sill	W	1	2.27 x 0.196 x 0.035	7 ea	Front and upper faces exposed
Notice board	W	6	0.9 x 0.6 x 0.018	5 ea	All faces except back
Moveable					
Desk (III) ~ full	W	2	See Figure 6.6.3.2	30 ea	All faces except back
Desk (III) ~ empty	W	2	See Figure 6.6.3.2	24 ea	All faces except back
Desk (II) ~ empty	W	1	See Figure 6.6.2.2	20 ea	All faces except back
Table (I)	W +S	5	See Figure 6.8.1.2	20 ea	All faces except the part underneath the table
Telephone	P + S + E	1	0.165 x 0.225	1 ea	Exposed from upper and side faces
Plastic chair (I)	P	5	0.5 x 0.45	12 ea	Exposed from upper and side faces
Plastic chair (II)	P + S	4	0.41 x 0.22	7 ea	Exposed from upper and side faces
Blinds	P	1	2.22 x 0.65	1.3 ea	Exposed from upper and side faces
Steel cabinet (I)	S	1	0.49 x 0.71 x 0.645	20 ea	N/A*
Contents of steel cabinet (I) ~ 37.5%	W	2	0.4 x 0.35 x 0.12	3 ea	All faces except the part underneath
Steel cabinet (II)	S	1	0.5 x 0.1 x 0.925	23 ea	N/A*
Steel cabinet (III)	S	2	0.505 x 0.62 x 1.32	30 ea	N/A*
Bundle of books and papers	W	1	0.3 x 0.235 x 0.175	6 ea	All faces except the part underneath
Rubbish bin	P	3	diameter = 0.3	1 ea	Exposed from upper and side faces
Papers	W	4	0.3 x 0.21 x 0.005	~ 0.2 ea	Exposed from upper and side faces
		1	0.9 x 0.6 x 0.0001	~ 0.1 ea	Exposed from upper and side faces

** N/A ~ steel materials are considered to be low fuel load in fire. Thus, surfaces are not involved in the fire.*

W = Wood, P = Plastic, S = Steel, E = Electrical, G = Glass.

Table 8.1.2.1: Summary descriptions of each fuel load in office E312.

The thinner portion of the cellulosic materials and almost all the non-cellulosic materials will have a shorter period of burning. The thicker portion of the cellulosic materials will undergo a longer period of burning before the complete burnout.

Figure 8.1.2.1 shows the layout of office E312.

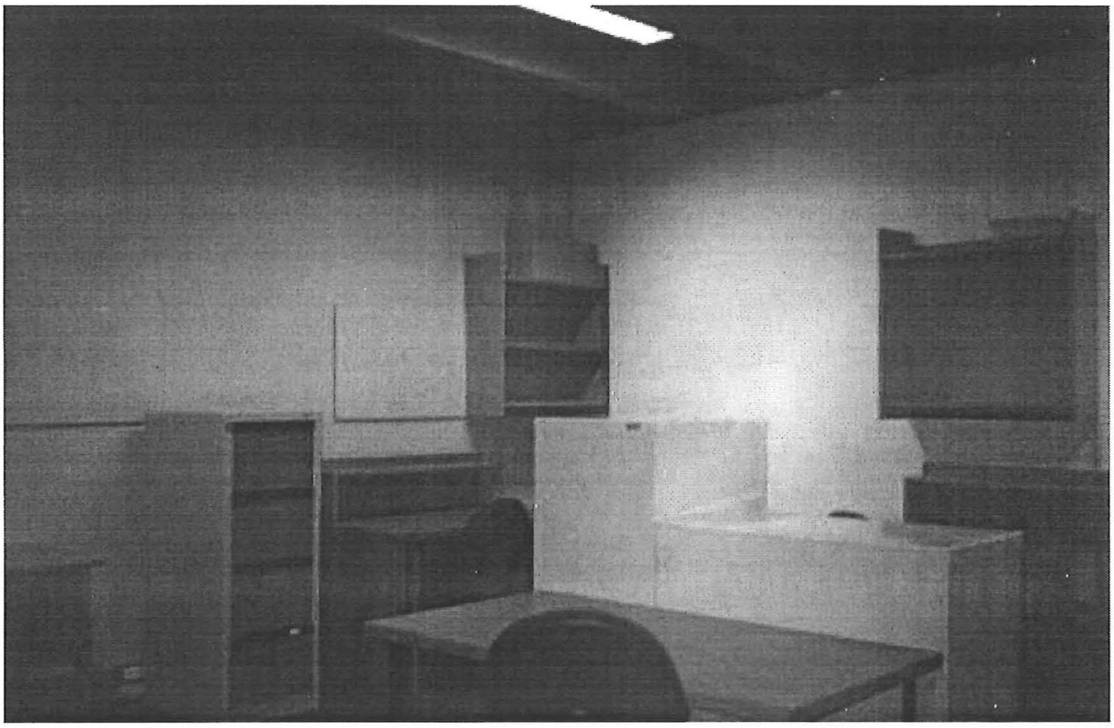


Figure 8.1.2.1: Layout of E312.

Figure 8.1.2.2 below shows the total amount of heat release rate available inside the office. The maximum value of the heat release rate is approximately 30 MW, based on the total exposed surface area of the fuel loads during a post-flashover fire, especially the large quantity of the exposed surface area of the carpet. However, the ventilation limit is only about 1.8 MW, based on the available ventilation from the small window. From the figure, it also can be seen that there is a large drop in the value of the heat release rate at the beginning of the burning duration. This is due to the complete burning of the thinner portions of the fuel loads. These include the carpet, the blind and all the thin, loose paper sheets lying inside the office. After the large drop, the values of heat release rate decrease according to the burning of the thicker portions of the fuel loads inside the office. The duration of burning is based on the thickest part of the items inside the office.

The fire load density for this office is only about 411 MJ/m^2. This is because besides the large area of the office, most of the furniture inside the office is empty. From Figure 8.1.2.2, one could see that there is quite a high portion of the heat release curve beyond the ventilation limit. Although the quantities of the burning fuel inside the office exceed the available limited ventilation, which is needed to support the burning, the outcome of the figure is actually based on the total amount of the exposed surface areas of the fuel loads to the fire.

As most of the furniture is empty, there is therefore more chance for each surface to be exposed to the fire. Consequently, this will increase the exposed surface area to the fire, which at the same time increase the value of the heat release rate.

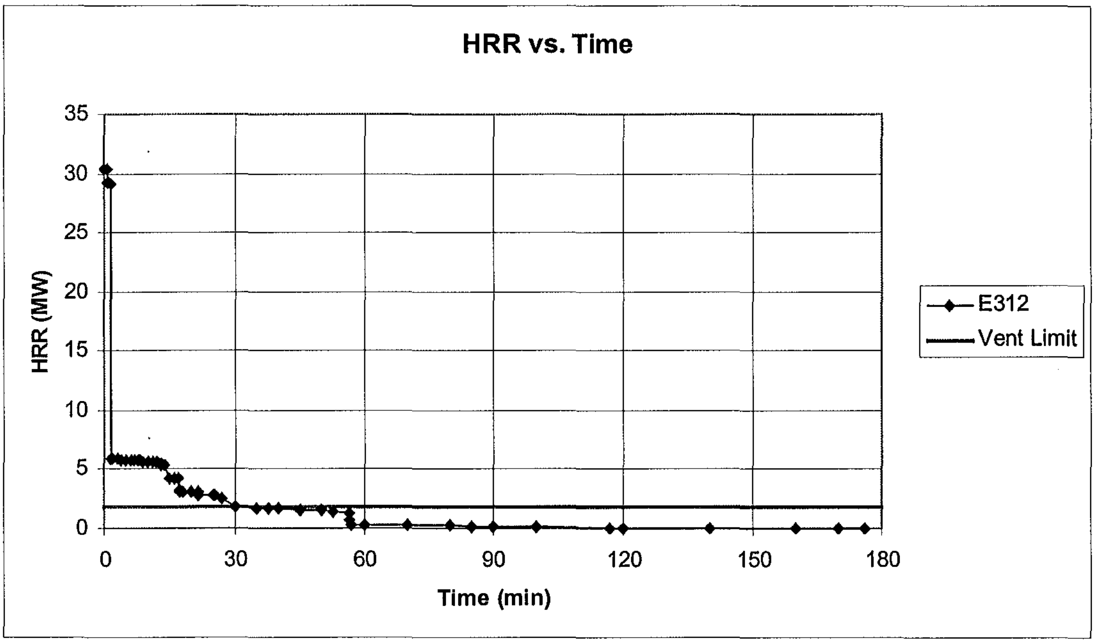


Figure 8.1.2.2: HRR vs. Time graph for fuel load inside office E312.

As mentioned earlier, there are two options in describing the outcome of the above figure. There is option (a), which suggested that the fuel is burning outside the building, at which the heat release rate curve is beyond the ventilation limit. From the figure above, it could be seen that most of the amount of heat release rate that is beyond the ventilation limit belongs to the thinner portion of the fuel, and where most of its surfaces are exposed to fire.

Figure 8.1.2.3 shows the concept described for option (b). The amount of heat release rate beyond the ventilation limit (E1) is shifted downward under the ventilation limit, and the original amount of energy under the ventilation limit (E2) is shifted to the right side of E1.

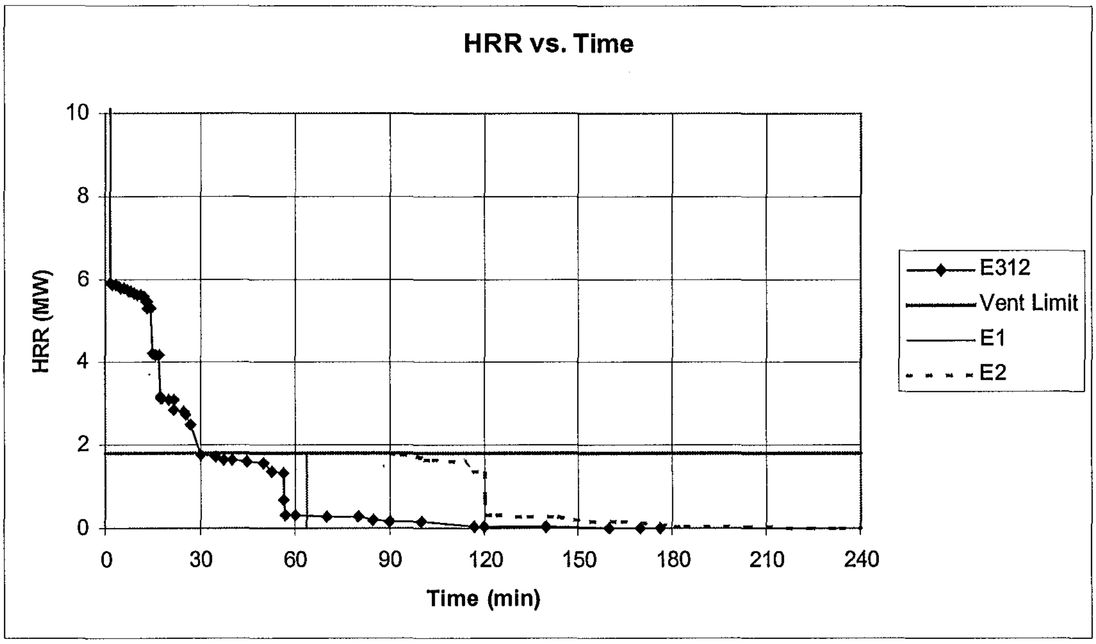


Figure 8.1.2.3:HRR vs. Time graph showing the shifting of E1 and E2 under the ventilation limit for office E312.

Figure 8.1.2.3 indicates that E1, which is nearer to the window, will be burned first before the burning of the further fuel loads (E2) takes place. By shifting and dividing the original curve into E1 and E2, the heat release rate curve will shift by 1 hour. This situation is different from the situation in office E306, as the amount of energy release beyond the ventilation limit (E1) is higher than the case before. Therefore, there is a larger shifting of the energy release curves under the ventilation limit. Besides that, the amount of air available in office E312 is less than in office E306.

8.1.3 E313

This office has a dimension of 5.89 m x 2.82 m. It has an opening to the outside with the dimension of 1.43 m x 1.72 m, assuming the glass broke during the post-flashover fire. Although it has a door with a dimension of approximately 1 m x 2.2 m, it is not considered to be a source of ventilation as it opens to a corridor, which has limited air, inside the building. Besides that, the door is considered to be closed during the modelling.

The office contains all sorts of fuel load ranging from wood materials to plastic materials, which are assumed to be ignited all at once during a post-flashover fire. Besides the mass and the dimensions, the exposed surface areas of each item are carefully assessed. Table 8.1.3.1 below shows the summary descriptions of each item.

Fire Load	Type	Quantity	Dimensions (m)	Mass (kg) (approx.)	Surface Area Exposed
Fixed					
Bookshelf (I) ~ 75% full	W	1	See Figure 6.2.1.2	27 ea	All faces except back
Bookshelf (I) ~ empty	W	2	See Figure 6.2.1.2	12 ea	All faces except back
Carpet	P	1	5.89 x 2.82	28 ea	Exposed from upper face
Door + frame	W	1	0.91 x 2.225 x 0.02	20 ea	Exposed from inside the compartment
Window sill	W	1	1.69 x 0.4 x 0.03	8 ea	Front and upper faces exposed
Notice board	W	4	0.9 x 0.6 x 0.018	5 ea	All faces except back
Moveable					
Desk (III) ~ full	W	3	See Figure 6.6.3.2	30 ea	All faces except back
Desk (II) ~ empty	W	1	See Figure 6.6.2.2	20 ea	All faces except back
Table (I)	W +S	4	See Figure 6.8.1.2	20 ea	All faces except the part underneath the table
Rubbish bin	P	1	diameter = 0.3	1 ea	Exposed from upper and side faces
Telephone	P + S + E	1	0.165 x 0.225	1 ea	Exposed from upper and side faces
Plastic chair (I)	P	3	0.5 x 0.45	12 ea	Exposed from upper and side faces
Plastic chair (II)	P + S	1	0.41 x 0.22	7 ea	Exposed from upper and side faces
Blinds	P	1	1.72 x 1.43	2.2 ea	Exposed from upper and side faces
Steel cabinet (I)	S	1	0.49 x 0.71 x 0.645	20 ea	N/A*
Contents of steel cabinet (I) ~ books	W	1	0.12 x 0.165 x 0.23	2.5 ea	All faces except the part underneath
Steel cabinet (III)	S	1	0.505 x 0.62 x 1.32	30 ea	N/A*
Contents of steel cabinet (III) ~ wooden blocks	W	1	0.38 x 0.19 x 0.045	4 ea	All faces except the part underneath
Bundle of books and papers	W	3	0.29 x 0.21 x 0.09	3 ea	All faces except the part underneath
Foams	P	8	0.51 x 0.51	2 ea	Exposed from upper and side faces
Blocks	W	24	0.05 x 0.1 x 0.1	0.5 ea	All faces except back and the underneath parts
Box of foams	P	1	0.39 x 0.26	2 ea	Exposed from upper and side faces
Other plastic things	P	1	0.9 x 0.75	3 ea	Exposed from upper and side faces
Roll of upholstered fabrics	P	2	diameter = 0.75	20 ea	Exposed from upper and side faces
Papers	W	2	0.3 x 0.21 x 0.03	~ 1 ea	Exposed from upper and side faces
		4	0.3 x 0.21 x 0.005	~ 0.2 ea	Exposed from upper and side faces
		1	0.9 x 0.6 x 0.0001	~ 0.1 ea	Exposed from upper and side faces

** N/A ~ steel materials are considered to be low fuel load in fire. Thus, surfaces are not involved in the fire.*

W = Wood, P = Plastic, S = Steel, E = Electrical, G = Glass.

Table 8.1.3.1: Summary descriptions of each fuel load in office E313..

During the modelling for each item available inside this office, it was found that most of the non-cellulosic materials and the thinner portion of the cellulosic materials will have a shorter burning period. The much thicker portion of the cellulosic materials will determine the total burning duration of the fuel inside the office.

Figure 8.1.3.1 shows the layout of office E313.

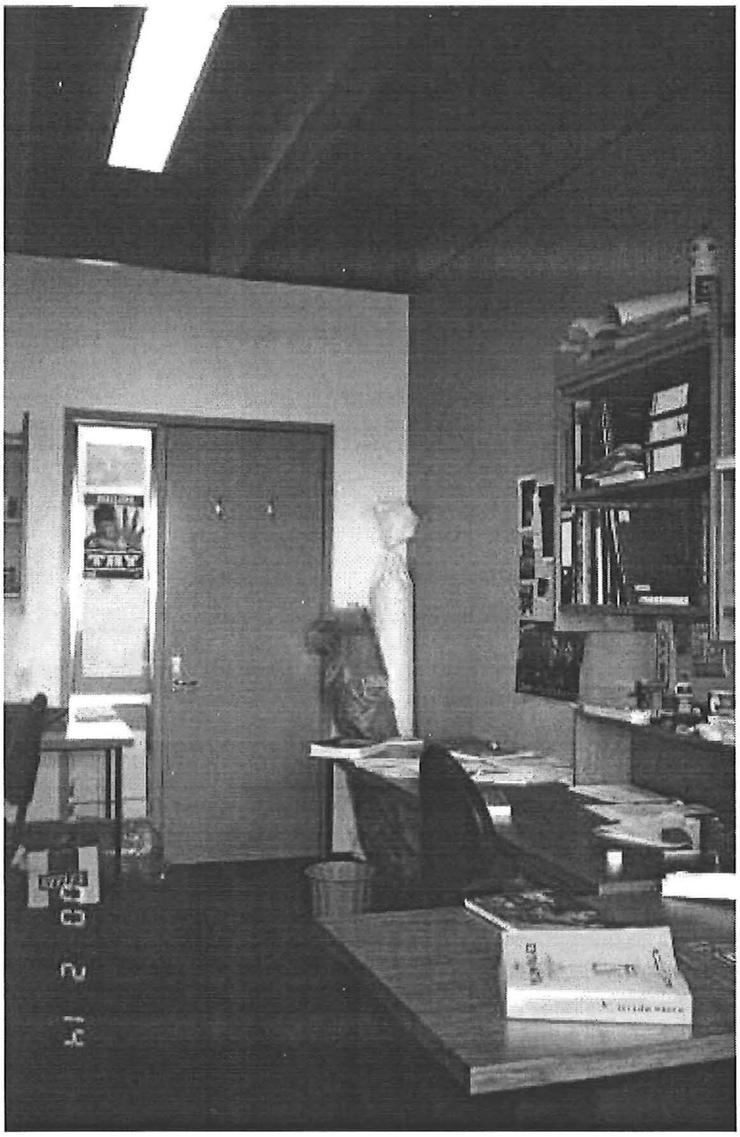


Figure 8.1.3.1: Layout of E313.

Figure 8.1.3.2 below shows the total amount of heat release rate available inside the office. The maximum value of the heat release rate is approximately 19 MW, based on the total exposed surface area of the fuel loads during a post-flashover fire, especially from the large area of the carpet. The ventilation limit is approximately 4.5

MW, based on the available ventilation from the opening to the open air in the office. From Figure 8.1.3.2, it can be seen that there is a large drop in the value of the heat release rate at the beginning of the burning duration. This is due to the complete burning of the thinner portions of the fuel loads. These include the carpet, the blind and all the thinner portions of the cellulosic materials such as the thin, loose paper sheets lying inside the office. After the large drop, the values of heat release rate decrease according to the burning of the thicker portions of the fuel loads inside the office. The total duration of burning is based on the thickest part of the fuel.

The fire load density for this office is about 795 MJ/m^2. Although this value shows that the amount of the fuel load inside the office is quite high, one would expect to see a higher portion of heat release curve predicted beyond the ventilation limit. This is due to the quantities of the burning fuel exceeding the available ventilation, which is needed to support the burning.

However, as seen in Figure 8.1.3.2, the result obtained is not as expected. This is because the outcome of the value of the heat release rate is based on the total amount of the exposed surface areas of the fuel loads to the fire, and not the total amount of the fuel loads (in kg) stored inside the office, as previously considered. Consequently, this means that the lesser the surface area exposed to the fire, the lower the value of the heat release rate.

As most of the furniture inside the office was full or partially full, (ie. bookshelf with books), this reduced the possibility of more surfaces of each furniture being exposed to the fire, which in turn reduced the value of the heat release rate.

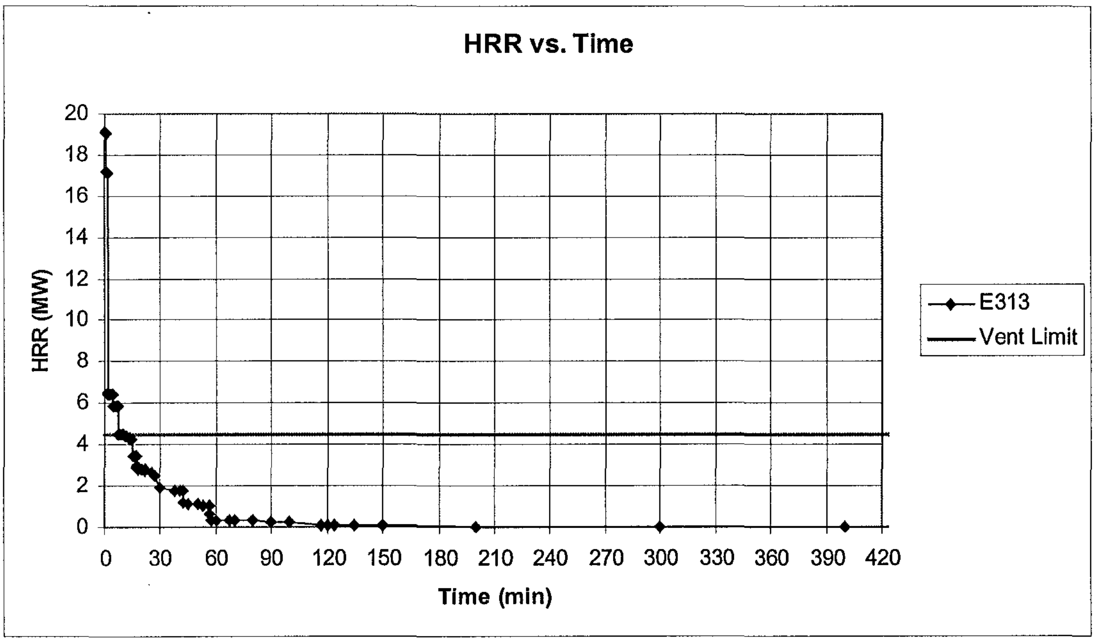


Figure 8.1.3.2: HRR vs. Time graph for fuel load inside office E313.

In order to explain the figure above, as before, option (a) indicates that the fuel is burning outside the building, at which the heat release rate curve is beyond the ventilation limit. This portion of the energy release is mostly given off by the burning of the thinner portion of the fuel, where most of the surfaces are exposed to fire.

Figure 8.1.3.3 shows the concept described for option (b). The amount of heat release rate beyond the ventilation limit (E1) is shifted downward, under the ventilation limit, and the original amount energy under the ventilation limit (E2) is shifted to the right side of E1.

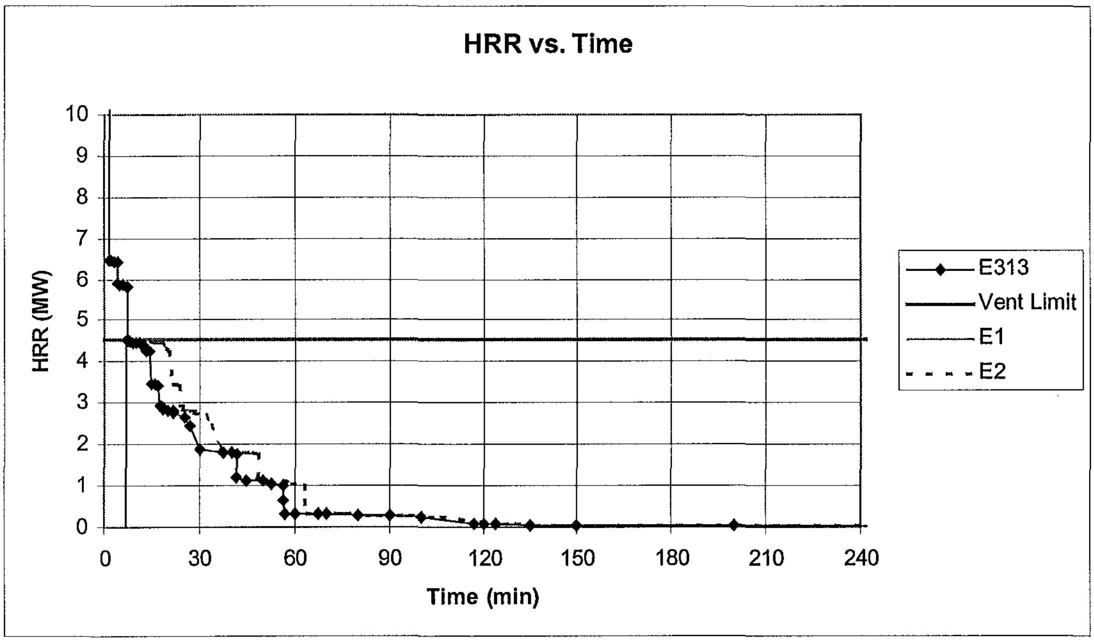


Figure 8.1.3.3:HRR vs. Time graph showing the shifting of E1 and E2 under the ventilation limit for office E313.

Figure 8.1.3.3 indicates that E1, which is nearer to the window, will be burned first before the burning of the further fuel loads (E2) takes place. There is only a small shift on the heat release curve, of approximately 1 minute.

8.1.4 E328

This office has same room and ventilation dimensions as office E313, which is 5.89 m x 2.82 m and 1.43 m x 1.72 m, respectively. The glass on the opening to the outside air is assumed to be broken during the post-flashover fire. Although this office has a door with a dimension of approximately 1 m x 2.2 m, it is not considered to be a source of ventilation as it opens to a corridor, which has limited air, inside the building. Furthermore, the door is considered to be in the closed position during the modelling.

The office contains all sorts of fuel load ranging from wood materials to plastic materials, which are assumed to be ignited all at once during a post-flashover fire. The mass, dimensions and the exposed surface areas of each item are carefully assessed. Table 8.1.4.1 below shows the summary descriptions of each item.

Fire Load	Type	Quantity	Dimensions (m)	Mass (kg) (approx.)	Surface Area Exposed
Fixed					
Carpet	P	1	5.89 x 2.82	28 ea	Exposed from upper face
Door + frame	W	1	0.91 x 2.225 x 0.02	20 ea	Exposed from inside the compartment
Window sill	W	1	1.69 x 0.4 x 0.03	8 ea	Front and upper faces exposed
Notice board	W	4	0.9 x 0.6 x 0.018	5 ea	All faces except back
Moveable					
Desk (III) ~ full	W	2	See Figure 6.6.3.2	30 ea	All faces except back
Desk (III) ~ empty	W	1	See Figure 6.6.3.2	24 ea	All faces except back
Table (I)	W +S	4	See Figure 6.8.1.2	20 ea	All faces except the part underneath the table
Rubbish bin	P	1	diameter = 0.3	1 ea	Exposed from upper and side faces
Telephone	P + S + E	1	0.165 x 0.225	1 ea	Exposed from upper and side faces
Plastic chair (I)	P	4	0.5 x 0.45	12 ea	Exposed from upper and side faces
Plastic chair (II)	P + S	3	0.41 x 0.22	7 ea	Exposed from upper and side faces
Blinds	P	1	1.72 x 1.43	2.2 ea	Exposed from upper and side faces
Steel cabinet (I)	S	2	0.49 x 0.71 x 0.645	20 ea	N/A*
Steel cabinet (IV)	S	1	0.46 x 1.32 x 0.64	25 ea	N/A*
Bookshelf (III) ~ 60% full	W	1	See Figure 6.2.3.2	50 ea	All faces except back
Computer	P + S + G + E	2	0.64 x 0.4	10 ea	Exposed from upper and side faces
Box of books and papers	W	3	0.25 x 0.4 x 0.42	18 ea	All faces except the part underneath
Other plastic things	P	1	0.6 x 0.4	3 ea	Exposed from upper and side faces
Papers	W	1	0.9 x 0.5 x 0.025	~ 2 ea	Exposed from upper and side faces
		4	0.3 x 0.21 x 0.005	~ 0.2 ea	Exposed from upper and side faces
		1	0.9 x 0.6 x 0.0001	~ 0.1 ea	Exposed from upper and side faces

** N/A ~ steel materials are considered to be low fuel load in fire. Thus, surfaces are not involved in the fire.*

W = Wood, P = Plastic, S = Steel, E = Electrical, G = Glass.

Table 8.1.4.1: Summary descriptions of each fuel load in office E328.

During the modelling for each item available inside office E328, besides the thinner portion of the cellulosic materials, it was found that almost all the non-cellulosic materials had a shorter burning period than the thicker portion of the cellulosic materials. Therefore, thermoplastic materials will burn out before wood materials.

Figure 8.1.4.1 shows the layout of office E328.

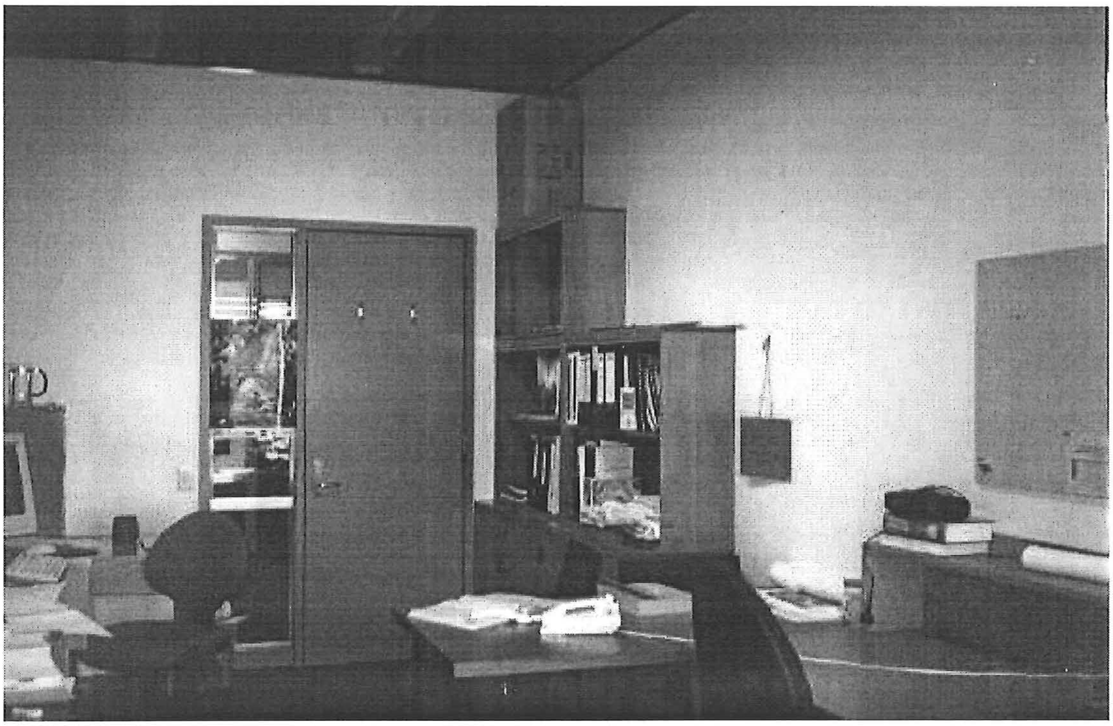


Figure 8.1.4.1: Layout of E328.

Figure 8.1.4.2 below shows the total amount of heat release rate available inside the office. The maximum value of the heat release rate is approximately 17.5 MW, based on the total exposed surface area of the fuel loads during a post-flashover fire. The ventilation limit is approximately 4.5 MW, as in office E313. There is a large drop in the value of the heat release rate at the beginning of the burning duration due to the complete burning of the thinner portions of the fuel loads, which include the carpet, the blind and the paper sheets lying inside the office. After the large drop, the values of heat release rate decrease according to the burning of the thicker portions of the fuel loads inside the office.

The fire load density for this office is approximately 801 MJ/m^2. Although this value shows that the amount of the fuel load inside the office is quite high, one would expect to see a higher portion of heat release curve predicted beyond the ventilation limit. This is due to the quantities of the burning fuel exceeding the available ventilation, which is needed to support the burning.

However, as seen in Figure 8.1.4.2, the result obtained is not as expected. This is because the outcome of the value of the heat release rate is based on the total amount of the exposed surface areas of the fuel loads to the fire, and not the total amount of the fuel loads (in kg) stored inside the office, as considered in previous surveys. Consequently, this means that the lesser the surface area exposed to the fire, the lower the value of the heat release rate.

As most of the furniture inside the office was full (ie. bookshelf full of books), simple shape of the fuel was adopted in predicting the surface area exposed for each complicated item. This reduced the possibility of more surfaces being exposed to the fire, which in term reduced the value of the heat release rate. This explanation can be supported by the data presented for single items in Chapter 6 (ie. see section 6.2).

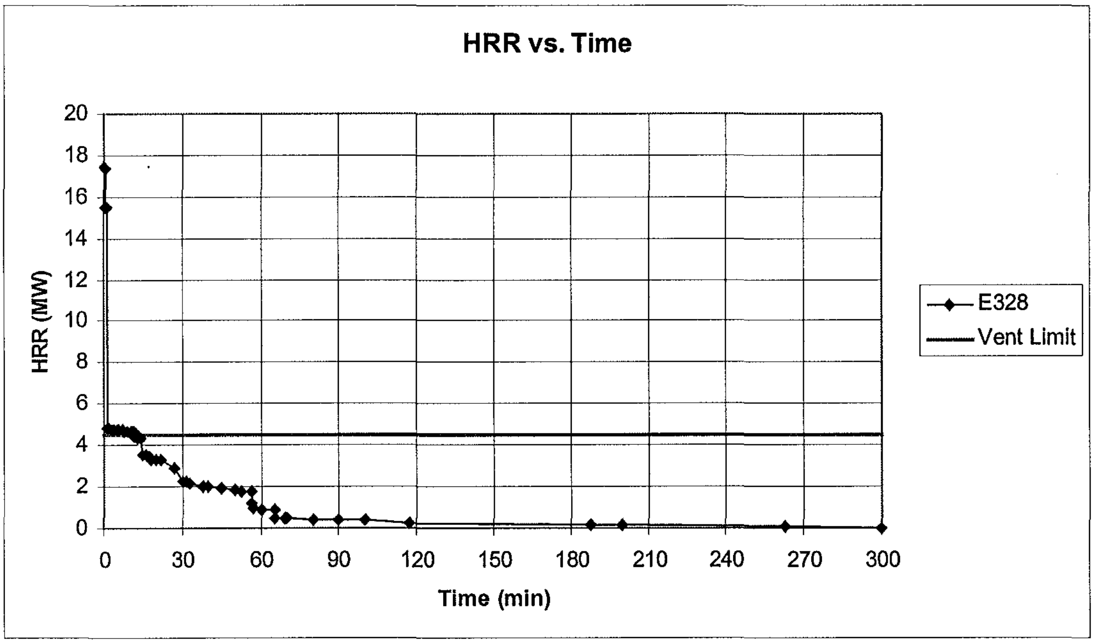


Figure 8.1.4.2: HRR vs. Time graph for fuel load inside office E328.

The behaviour of the figure above, for option (a) indicates that during the post-flashover fire, due to the limited air supply to support the burning, some fuel is going to burn outside the building. This is showed by the heat release curve, which is beyond the ventilation limit. However, this portion of the energy release is given off mostly by the burning of the thinner portion of the fuel, with their surfaces exposed to fire.

Figure 8.1.4.3 shows the concept described for option (b). As before, the amount of heat release rate beyond the ventilation limit (E1) is shifted downward, under the ventilation limit, and the original amount energy under the ventilation limit (E2) is shifted to the right side of E1.

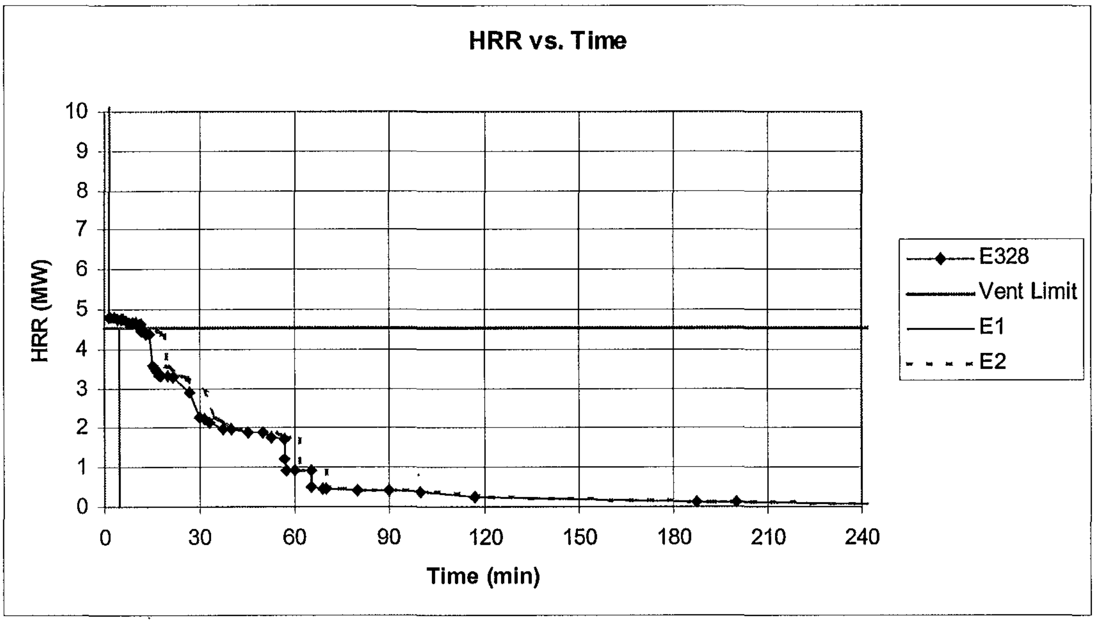


Figure 8.1.4.3:HRR vs. Time graph showing the shifting of E1 and E2 under the ventilation limit for office E328.

There is 5 minutes shift in the heat release rate curve. The trend of E1 and E2 shown in Figure 8.1.4.3 indicates that E1, which is nearer to the window, will be burned first before the burning of the fuel loads E2, which are further away from the window takes place.

8.2 University Rooms

8.2.1 Andy's Office

Andy's office has an area of 5.47 m x 3.1 m. It has one opening to the open air with 2.28 m width and 1.49 m height. The glass on the opening to the outside air is assumed to be broken during the post-flashover fire. It also has a door with a dimension of approximately 1 m x 2.2 m, but it is not considered to be a source of ventilation as it opens to a corridor, which has limited air, inside the building. Furthermore, the door is considered to be closed during a fire.

The office contains all sorts of fuel load ranging from wood materials, such as bookshelf full of books to other plastic materials, which are assumed to be fully ignited during a post-flashover fire. The exposed surface areas of each item are carefully assessed in order to predict the possible value of heat release inside the office. Table 8.2.1.1 below shows the summary descriptions of each item inside the office.

Fire Load	Type	Quantity	Dimensions (m)	Mass (kg) (approx.)	Surface Area Exposed
Fixed					
Carpet	P	1	5.47 x 3.1	28 ea	Exposed from upper face
Door + frame	W	1	0.91 x 2.225 x 0.02	20 ea	Exposed from inside the compartment
Window sill	W	1	2.28 x 0.03 x 0.2	8 ea	Front and upper faces exposed
Notice board	W	2	0.9 x 0.6 x 0.018	5 ea	All faces except back
Moveable					
Desk (II) ~ full	W	1	See Figure 6.6.2.2	26 ea	All faces except back
Table (III)	W +S	2	0.67 x 0.52 x 0.04	15 ea	All faces except the part underneath the table
Coffee Table	W +S	1	0.51 x 0.76 x 0.04	8 ea	All faces except the part underneath the table
Rubbish bin	S	1	diameter = 0.3	1 ea	N/A
Telephone	P + S + E	1	0.165 x 0.225	1 ea	Exposed from upper and side faces
Cupboard (I) ~ empty	W	2	See Figure 6.5.1.2	30 ea	All faces except back
Contents in cupboard (I)	W	2	0.9 x 0.21 x 0.3	15 ea	All faces except the part underneath
Contents in cupboard (I)	P	2	0.19 x 0.8	6 ea	Exposed from upper and side faces
Plastic chair (I)	P	1	0.5 x 0.45	12 ea	Exposed from upper and side faces
Plastic chair (II)	P + S	4	0.41 x 0.22	7 ea	Exposed from upper and side faces
Steel cabinet (III)	S	3	0.505 x 0.62 x 1.32	30 ea	N/A*
Contents of steel cabinet (III)	W	12	0.31 x 0.5 x 0.215	15 ea	All faces except the part underneath
Bookshelf ~ overall 80% full (larger version of Bookshelf (II))	W	1	See Figure 6.2.2.2	100 ea	All faces except back
Computer	P + S + G + E	2	0.64 x 0.4	10 ea	Exposed from upper and side faces
Blinds	P	1	2.28 x 1.49	3 ea	Exposed from upper and side faces
		1	0.42 x 2.23	1 ea	Exposed from upper and side faces
Other plastic things	P	1	0.8 x 0.5	10 ea	Exposed from upper and side faces
Pictures	W	20	0.24 x 0.34 x 0.015	1 ea	Exposed from front and side faces
Books and papers	W	10	0.3 x 0.215 x 0.15	5 ea	All faces except the part underneath
Computer table	W + S	1	0.64 x 0.8 x 0.3	20 ea	All faces except the part underneath
Lump of blocks	W	1	0.55 x 0.45 x 0.42	30 ea	All faces except the part underneath
Bookshelf with blocks	W	1	0.9 x 0.2 x 0.3	50 ea	All faces except back
Papers	W	1	0.1 x 0.4 x 0.01	~ 1 ea	Exposed from upper and side faces
		1	0.6 x 0.5 x 0.01	~ 1.5 ea	Exposed from upper and side faces
		1	0.76 x 0.5 x 0.005	~ 0.9 ea	Exposed from upper and side faces
		1	0.9 x 0.6 x 0.0001	~ 0.1 ea	Exposed from upper and side faces

** N/A ~ steel materials are considered to be low fuel load in fire. Thus, surfaces are not involved in the fire.*

W = Wood, P = Plastic, S = Steel, E = Electrical, G = Glass.

Table 8.2.1.1: Summary descriptions of each fuel load in Andy's office.

During the modelling for each item available inside the office, it was found that besides the thinner portion of the cellulosic materials, such as thin, loose paper sheets, almost all the non-cellulosic materials have a shorter burning period than the thicker portion of the cellulosic materials. The thickest portion of the fuel inside the office will determine the duration of burning.

Figure 8.2.1.1 shows the layout of Andy's office.

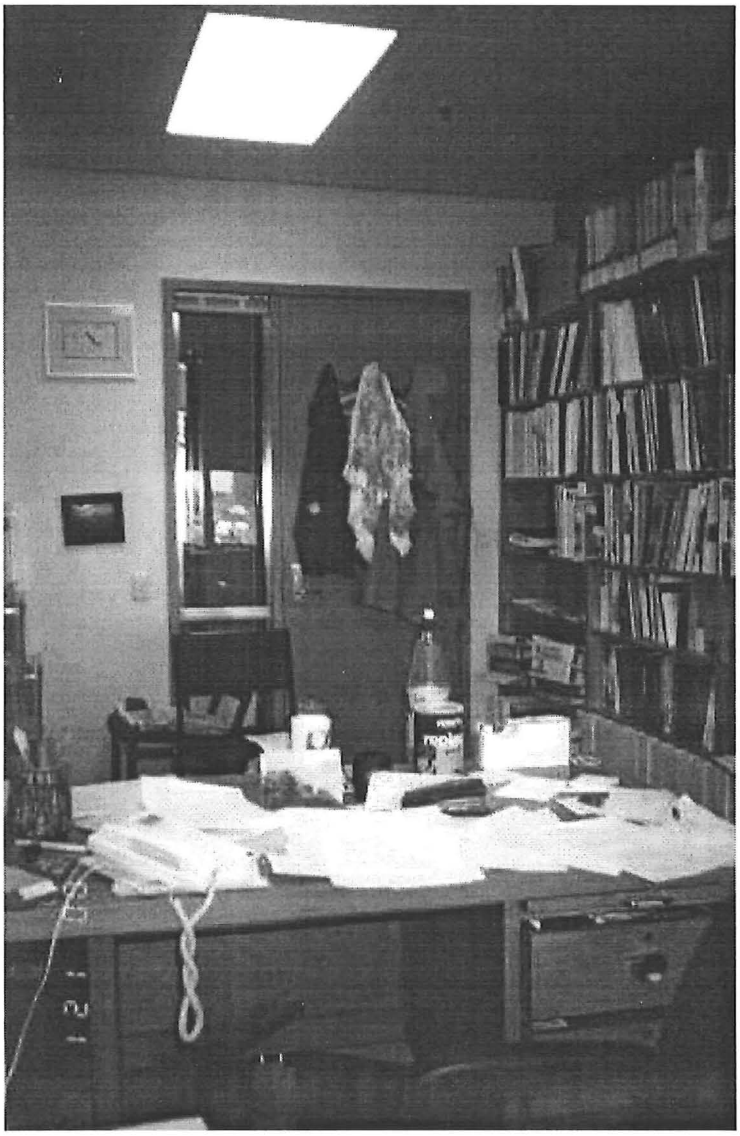


Figure 8.2.1.1: Layout of Andy's office.

Figure 8.2.1.2 below shows the total amount of heat release rate available inside the office. The maximum value of the heat release rate is approximately 18.9 MW, based on the total exposed surface area of the fuel loads during a post-flashover fire. The ventilation limit is approximately 6.4 MW. There is a large drop in the value of the heat release rate a few minutes after flashover due to the complete burning of the thinner portions of the fuel loads, which include the carpet, the blind and the paper sheets lying inside the office. The high value of the heat release rate is due to large exposed surface area initially. After the drop, the values of the heat release rate decrease according to the burning of the thicker portions of the fuel loads inside the office. The thickest part of the fuel will determine the duration of burning.

The fire load density for this office is approximately 1180 MJ/m^2. Although this value shows that the amount of the fuel load inside the office is quite high, one would expect to see a higher portion of heat release curve predicted beyond the ventilation limit. This is due to the quantities of the burning fuel exceeding the available ventilation which is needed to support the burning.

However, as seen in Figure 8.2.1.2, the result obtained is not as expected. This is because the outcome of the value of the heat release rate is based on the total amount of the exposed surface areas of the fuel loads to the fire, and not the total amount of the fuel loads (in kg) stored inside the office. Consequently, this means that the lesser the surface area exposed to the fire, the lower the value of the heat release rate.

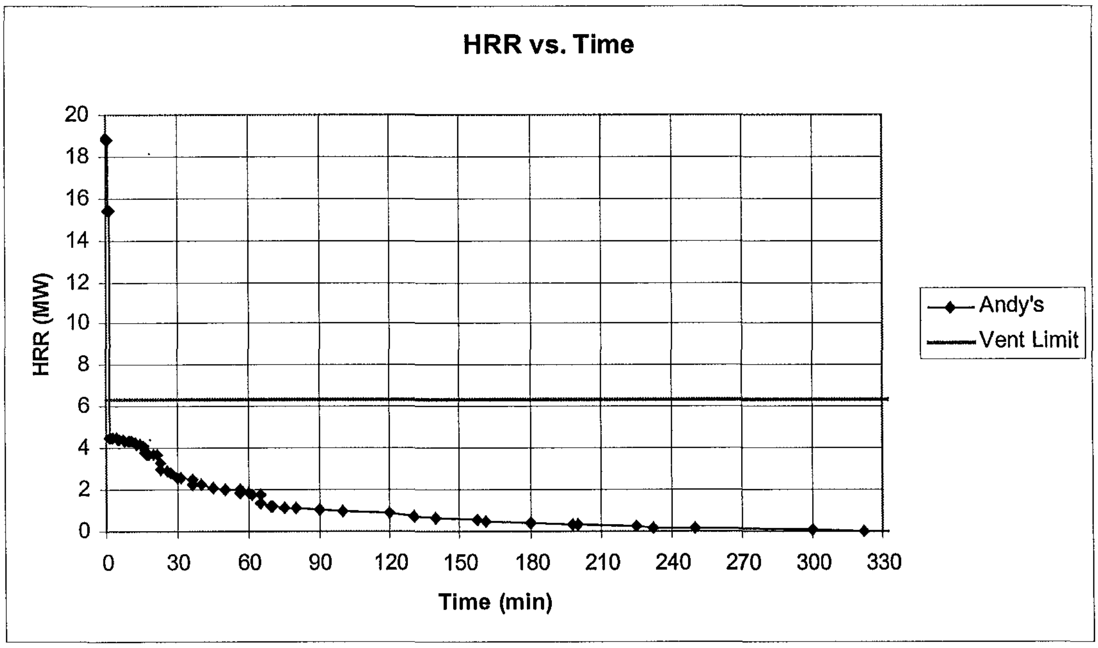


Figure 8.2.1.2: HRR vs. Time graph for fuel load inside Andy's office.

In order to explain the behaviour of Figure 8.2.1.2 above, option (a) indicates that during the post-flashover fire, due to the limited air supply inside the office to support the burning, all the unburnt fuel is going to burn outside the building, which normally seen as flame burning from the opening. This is showed by the heat release curve, which is beyond the ventilation limit. This portion of the energy release is given off mostly by the burning of the thinner portion of the fuel, with large amount of the surfaces exposed to fire initially.

Figure 8.2.1.3 shows the concept described for option (b). As before, the amount of heat release rate beyond the ventilation limit (E1) is shifted downward, under the ventilation limit, and the original amount energy under the ventilation limit (E2) is shifted to the right side of E1.

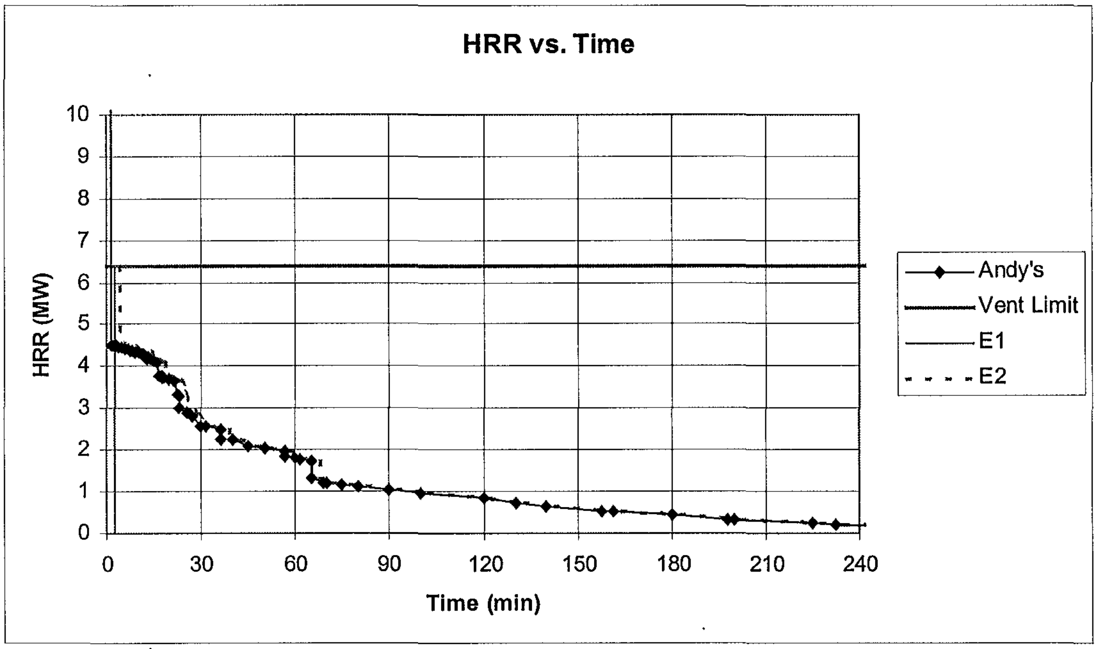


Figure 8.2.1.3:HRR vs. Time graph showing the shifting of E1 and E2 under the ventilation limit for Andy's office.

By shifting and dividing the original curve into E1 and E2, the heat release curve will shift by only 2 minutes. The trend of E1 and E2 shown in Figure 8.2.1.3 indicates that the fuel nearer to the opening, which in this case is E1, will be burned first before the burning of the fuel loads E2, which are further away from the window.

8.2.2 Catherine's Office

The dimensions of the office and the ventilation are 5.9m x 3.1m and 2.61m x 1.54m, respectively. The glass on the opening to the outside air is assumed to be broken during a post-flashover fire. Although the office has a door with a dimension of approximately 1 m x 2.2 m, it is not considered to be a source of ventilation as it opens to a corridor, which has limited air, inside the building. Furthermore, the door is considered to be closed during the modelling.

The office contains all sorts of fuel load, which are assumed to be ignited all at once during a post-flashover fire. The exposed surface areas of each item are carefully assessed. Table 8.2.2.1 below shows the summary descriptions of each item.

Fire Load	Type	Quantity	Dimensions (m)	Mass (kg) (approx.)	Surface Area Exposed
Fixed					
Carpet	P	1	5.9 x 3.1	31 ea	Exposed from upper face
Door + frame	W	1	0.91 x 2.225 x 0.02	20 ea	Exposed from inside the compartment
Window sill	W	1	2.61 x 0.03 x 0.2	8 ea	Front and upper faces exposed
Notice board	W	1	0.9 x 0.6 x 0.018	5 ea	All faces except back
Built-in cupboard (I) ~ (similar version to Bookshelf (I))	W	1	See Figure 6.2.1.2	20 ea	All faces except back
Built-in cupboard (II)	W	2	1 x 0.29 x 0.025	3 ea	All faces except back
Moveable					
Desk (II) ~ full	W	2	See Figure 6.6.2.2	26 ea	All faces except back
Table (IV)	W	1	Table surface ~ 0.77 x 0.6 x 0.06 Legs ~ 0.05 x 0.04 x 0.64	15 ea	All faces except the part underneath the table
Table (III)	W +S	3	0.67 x 0.52 x 0.04	15 ea	All faces except the part underneath the table
Rubbish bin	P	1	diameter = 0.3	1 ea	Exposed from upper and side faces
Telephone	P + S + E	1	0.165 x 0.225	1 ea	Exposed from upper and side faces
Cupboard (I) ~ empty	W	1	See Figure 6.5.1.2	30 ea	All faces except back
Contents in cupboard (I)	W	2	0.9 x 0.21 x 0.3	15 ea	All faces except the part underneath
Plastic chair (I)	P	1	0.5 x 0.45	12 ea	Exposed from upper and side faces
Plastic chair (II)	P + S	2	0.41 x 0.22	7 ea	Exposed from upper and side faces
Plastic chair (III)	P + W	1	0.49 x 0.3	5 ea	Exposed from upper and side faces
Steel cabinet (III)	S	1	0.505 x 0.62 x 1.32	30 ea	N/A*
Contents of steel cabinet (III)	W	4	0.31 x 0.4 x 0.215	5 ea	All faces except the part underneath
Steel cabinet (IV)	S	1	0.46 x 1.32 x 0.64	25 ea	N/A*
Contents of steel cabinet (IV)	W	3	0.31 x 0.5 x 0.215	5 ea	All faces except the part underneath
Blinds	P	1	2.61 x 1.54	3 ea	Exposed from upper and side faces
		1	0.42 x 2.23	1 ea	Exposed from upper and side faces
Computer	P + S + G + E	1	0.64 x 0.4	10 ea	Exposed from upper and side faces
Computer table	W + S	1	0.64 x 0.8 x 0.3	20 ea	All faces except the part underneath
Other plastic things	P	1	0.67 x 0.6	10 ea	Exposed from upper and side faces
		5	0.3 x 0.4	2 ea	Exposed from upper and side faces
Books and papers	W	10	0.3 x 0.2 x 0.15	4 ea	All faces except the part underneath
Papers	W	1	0.1 x 0.4 x 0.01	~ 1 ea	Exposed from upper and side faces
		1	0.6 x 0.5 x 0.01	~ 1.5 ea	Exposed from upper and side faces
		1	0.76 x 0.5 x 0.005	~ 0.9 ea	Exposed from upper and side faces
		1	0.9 x 0.6 x 0.0001	~ 0.1 ea	Exposed from upper and side faces

** N/A ~ steel materials are considered to be low fuel load in fire. Thus, surfaces are not involved in the fire.*

W = Wood, P = Plastic, S = Steel, E = Electrical, G = Glass.

Table 8.2.2.1: Summary descriptions of each fuel load in Catherine's office.

The thinner portion of the cellulosic materials, as well as most of the non-cellulosic materials will burn out before the thicker portion of the cellulosic materials.

Figure 8.2.2.1 shows the layout of Catherine's office.

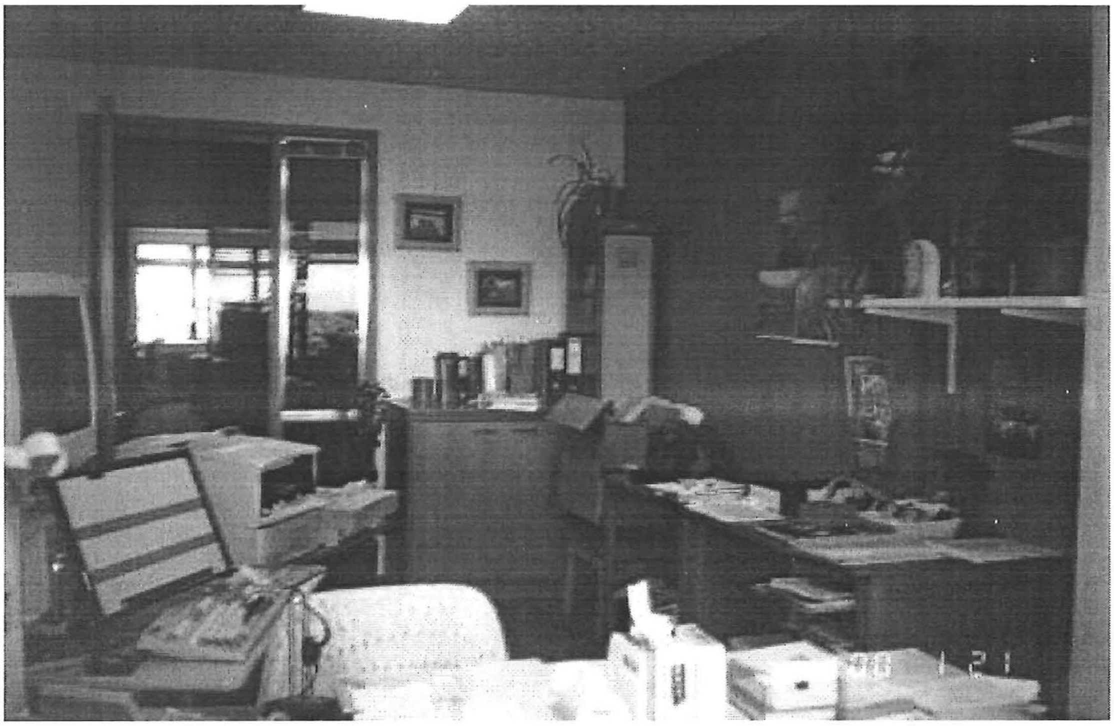


Figure 8.2.2.1: Layout of Catherine's office.

Figure 8.2.2.2 below shows the heat release curve of the office. The maximum value of the heat release rate is approximately 19 MW, based on the total exposed surface area of the fuel loads during a post-flashover fire. The ventilation limit is about 7.7 MW. Some time after the exposure, there is a large drop in the value of the heat release rate. This is due to the complete burning of the thinner portions of the fuel loads. The high value of heat release rate is due to large surface area of the fuel being exposed to the fire initially. After the large drop, the values of heat release rate decrease according to the burning of the thicker portions of the fuel loads inside the office.

The fire load density for this office is approximately 651 MJ/m^2. Although this value shows that the amount of the fuel load inside the office is quite high, one would expect to see a higher portion of heat release curve predicted beyond the ventilation limit. This is due to the quantities of the burning fuel exceeding the available ventilation which is needed to support the burning.

However, as seen in Figure 8.2.2.2, the result obtained is not as expected. This is because the outcome of the value of the heat release rate is based on the total amount of the exposed surface areas of the fuel loads to the fire, and not the total amount of the fuel loads (in kg) stored inside the office. Consequently, this means that the lesser the surface area exposed to the fire, the lower the value of the heat release rate.

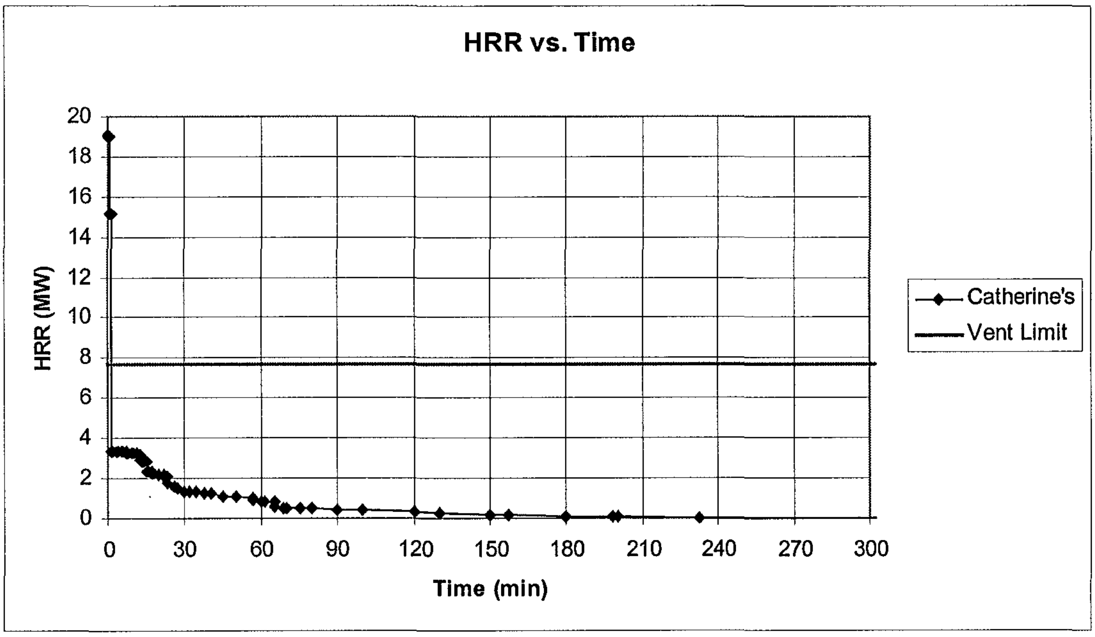


Figure 8.2.2.2: HRR vs. Time graph for fuel load inside Catherine's office.

For option (a), the behaviour of the above figure indicates that during the post-flashover fire, due to the limited air supply to support the burning, all the unburnt fuel is going to burn outside the building. This is showed by the heat release curve, which is beyond the ventilation limit. However, this portion of the energy release is given off by most of the burning of the thinner portion fuels, with large surface area exposed initially.

Figure 8.2.2.3 shows the concept described for option (b). The amount of heat release rate beyond the ventilation limit (E1) is shifted downward, under the ventilation limit, and the original amount energy under the ventilation limit (E2) is shifted to the right side of E1.

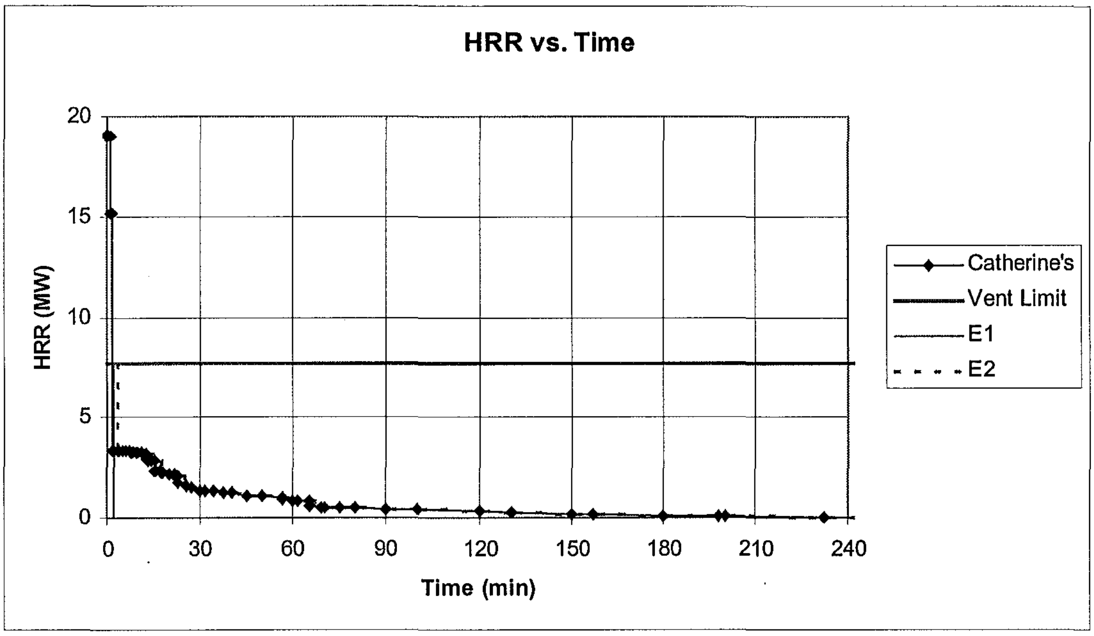


Figure 8.2.2.3:HRR vs. Time graph showing the shifting of E1 and E2 under the ventilation limit for Catherine's office.

Again the shifting of the heat release rate curve is not significant. The trend of E1 and E2 shown in Figure 8.2.2.3 indicates a concept that E1, which is nearer to the window, will be burned first before the burning of the fuel loads E2, which are further away from the window takes place.

8.2.3 Charley's Office

Charley's office has a room dimension of 5.56 m x 3.04 m. It has two windows, each with dimension of approximately 2.27 m x 1.49 m. The glass on the windows is assumed to be broken during the post-flashover fire. Although the office has a door with a dimension of approximately 1 m x 2.2 m, it is not considered to be a source of ventilation as it opens to a corridor which has limited air, inside the building. Besides that, the door is assumed to be closed during the modelling.

The office contains all sorts of fuel load. Table 8.2.3.1 below shows the summary descriptions of each item. The exposed surface areas of each item are also carefully assessed.

Fire Load	Type	Quantity	Dimensions (m)	Mass (kg) (approx.)	Surface Area Exposed
Fixed					
Carpet	P	1	5.56 x 3.04	28 ea	Exposed from upper face
Door + frame	W	1	0.91 x 2.225 x 0.02	20 ea	Exposed from inside the compartment
Window sill	W	2	2.27 x 0.2 x 0.03	7.5 ea	Front and upper faces exposed
Notice board	W	1	0.9 x 0.6 x 0.018	5 ea	All faces except back
Built-in bookshelf ~ full (similar version of Bookshelf (I))	W	1	See Figure 6.2.1.2	25 ea	All faces except back
Moveable					
Steel cabinet (III)	S	5	0.505 x 0.62 x 1.32	30 ea	N/A*
Contents of steel cabinet (III)	W	20	0.31 x 0.5x 0.215	5 ea	All faces except the part underneath
Small TV	P + S + G + E	1	0.35 x 0.3	8 ea	Exposed from upper and side faces
VCR	P + S + E	1	0.4 x 0.35	5 ea	Exposed from upper and side faces
Plastic chair (I)	P	2	0.5 x 0.45	12 ea	Exposed from upper and side faces
Plastic chair (II)	P + S	4	0.41 x 0.22	7 ea	Exposed from upper and side faces
Coffee Table	W +S	1	0.51 x 0.76 x 0.04	8 ea	All faces except the part underneath the table
Cupboard (I) ~ empty	W	1	See Figure 6.5.1.2	30 ea	All faces except back
Contents in cupboard (I)	W	2	0.9 x 0.21 x 0.3	15 ea	All faces except the part underneath
Desk (II) ~ full	W	1	See Figure 6.6.2.2	26 ea	All faces except back
Cupboard (III) ~ full	W	1	0.91 x 0.9 x 0.54	70 ea	All faces except back
Rubbish bin	P	1	diameter = 0.3	1 ea	Exposed from upper and side faces
Steel cabinet (I)	S	1	0.49 x 0.71 x 0.645	20 ea	N/A*
Contents of steel cabinet (I)	W	2	0.6 x 0.3 x 0.21	5 ea	All faces except the part underneath
Computer table	W + S	1	0.64 x 0.8 x 0.3	20 ea	All faces except the part underneath
Computer	P + S + G + E	1	0.64 x 0.4	10 ea	Exposed from upper and side faces
Telephone	P + S + E	1	0.165 x 0.225	1 ea	Exposed from upper and side faces
Cupboard (IV) ~ full	W	1	0.49 x 1.97 x 0.5	50 ea	All faces except back
Printer	P + S + E	1	0.35 x 0.23	4 ea	Exposed from upper and side faces
Bookshelf ~ overall full (larger version of Bookshelf (II))	W	1	See Figure 6.2.2.2	85 ea	All faces except back
Books and papers on steel cabinet	W	1	2.5 x 0.65 x 0.4	35 ea	Exposed from upper and side faces
Books on window sill	W	1	1.51 x 0.2 x 0.26	25 ea	All faces except the hidden faces
Box of books and papers	W	4	0.4 x 0.35 x 0.33	10 ea	All faces except the part underneath
Box of videos	P	1	0.3 x 0.26	2 ea	Exposed from upper and side faces
Pictures	W	3	0.6 x 0.66 x 0.015	5 ea	Exposed from front and side faces
		5	0.24 x 0.34 x 0.015	1 ea	Exposed from front and side faces
Blinds	P	2	2.27 x 1.49	3 ea	Exposed from upper and side faces
Other plastic things	P	1	2 x 0.2	4 ea	Exposed from upper and side faces
		1	0.3 x 0.45	2 ea	Exposed from upper and side faces
		1	0.86 x 0.29	6 ea	Exposed from upper and side faces
		4	0.3 x 0.21	1 ea	Exposed from upper and side faces
Clothes	P	1	0.91 x 0.1	2 ea	Exposed from front and side faces
Papers	W	5	1 x 0.35 x 0.02	~ 3 ea	Exposed from upper and side faces
		1	0.9 x 0.6 x 0.0001	~ 0.1 ea	Exposed from upper and side faces

** N/A ~ steel materials are considered to be low fuel load in fire. Thus, surfaces are not involved in the fire.*

W = Wood, P = Plastic, S = Steel, E = Electrical, G = Glass.

Table 8.2.3.1: Summary descriptions of each fuel load in Charley's office.

During the modelling for each item available inside Charley's office, besides the thinner portion of the cellulosic materials, such as thin, loose paper sheets, it is found that almost all the non-cellulosic materials had a shorter burning period than the thicker portion of the cellulosic materials. In other words, thermoplastic materials will burn out before wood materials.

Figure 8.2.3.1 shows the layout of Charley's office.

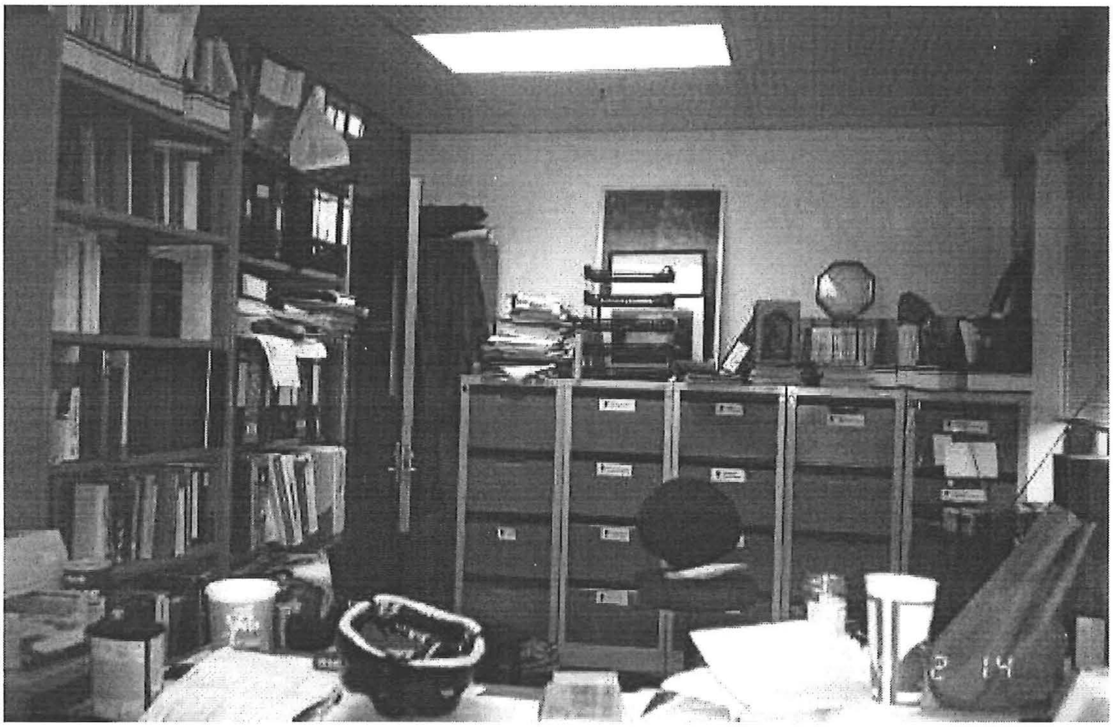


Figure 8.2.3.1: Layout of Charley's office.

Figure 8.2.3.2 below shows the total amount of heat release rate available inside the office. The maximum value of the heat release rate is approximately 22.5 MW, based on the total exposed surface area of the fuel loads during a post-flashover fire. The ventilation limit is about 12.5 MW. There is a large drop in the value of the heat release rate at the beginning of the burning duration due to the complete burning of the thinner portions of the fuel loads, with large amount of total surface area exposed to the fire initially. After the large drop, the values of heat release rate decrease according to the burning of the thicker portions of the fuel loads inside the office. The thickest part of the fuel will determine the duration of burning.

The fire load density for this office is about 2400 MJ/m^2. Although this value shows that the amount of the fuel load inside the office is very high, one would expect to see a higher portion of heat release curve predicted beyond the ventilation limit. This is due to the quantities of the burning fuel exceeding the available ventilation which is needed to support the burning.

However, as seen in Figure 8.2.3.2, the result obtained is not as expected. This is because the outcome of the value of the heat release rate is based on the total amount of the exposed surface areas of the fuel loads to the fire, and not the total amount of the fuel loads (in kg) stored inside the office, as previously conducted. Consequently, this means that the lesser the surface area exposed to the fire, the lower the value of the heat release rate.

As most of the furniture inside the office was full (ie. bookshelf full of books), simple shape of the fuel was adopted in predicting the surface area exposed for each complicated item. This reduced the possibility of more surfaces being exposed to the fire, which in turn reduced the value of the heat release rate. This explanation can be supported by the data presented for single items in Chapter 6 (ie. see section 6.2).

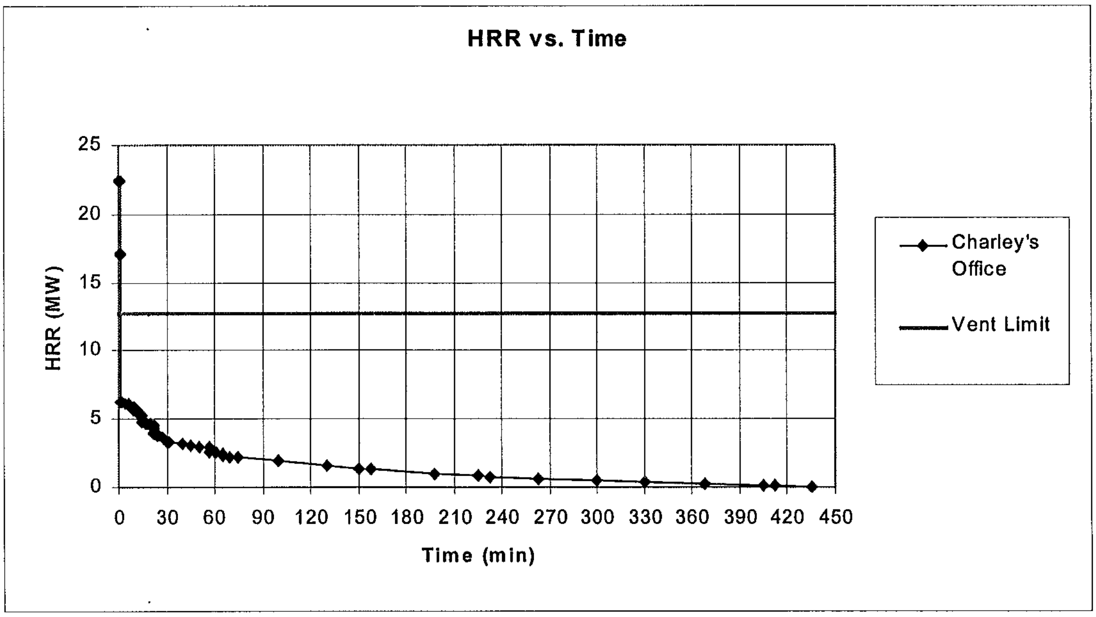


Figure 8.2.3.2: HRR vs. Time graph for fuel load inside Charley' office.

In order to explain the behaviour of the figure above, option (a) indicates that during the post-flashover fire, due to the limited air supply to support the burning, some fuel is going to burn outside the building. This is showed by the heat release curve, which is beyond the ventilation limit. From the figure, this portion of the energy release is given off by most of the burning of the thinner portion of the fuel, with their surfaces exposed to the fire.

Figure 8.2.3.3 shows the concept described for option (b). As before, the amount of heat release rate beyond the ventilation limit (E1) is shifted downward, under the ventilation limit, and the original amount energy under the ventilation limit (E2) is shifted to the right side of E1.

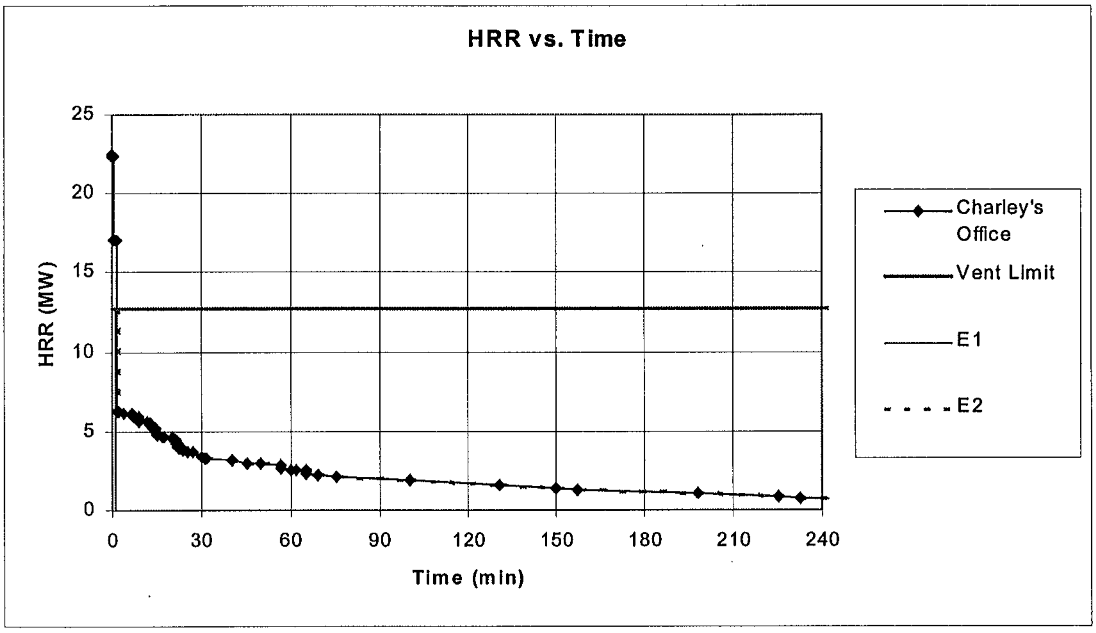


Figure 8.2.3.3:HRR vs. Time graph showing the shifting of E1 and E2 under the ventilation limit for Charley's office.

The difference between the duration of burning before the shift and after the shift is not significant. The trend of E1 and E2 shown in Figure 8.2.3.3 indicates that E1, which is nearer to the window, will be burned first before the burning of the fuel loads E2, which are further away from the window.

8.2.4 Civil Engineering Computer Lab

The room area of the Civil Engineering computer lab is approximately 14.85 m x 14.58 m. It contains only computers, plastic type chairs and computer tables. It has a lot of ventilation openings, which the glass is assumed to be broken during the post-flashover fire. The room also has a door with a dimension of approximately 2m x

2.2m, but it is not considered to be a source of ventilation as it opens to a corridor, which has limited air, inside the building. Furthermore, the door is considered to be in the closed position during the modelling.

Table 8.2.4.1 below shows the summary descriptions of each item, with their exposed surface areas carefully assessed.

Fire Load	Type	Quantity	Dimensions (m)	Mass (kg) (approx.)	Surface Area Exposed
Fixed					
Carpet	P	1	14.85 x 14.575	100 ea	Exposed from upper face
Door + frame	W	2	0.91 x 2.225 x 0.02	20 ea	Exposed from inside the compartment
Moveable					
Computer	P + S + G + E	53	0.64 x 0.4	10 ea	Exposed from upper and side faces
Plastic chair (I)	P	53	0.5 x 0.45	12 ea	Exposed from upper and side faces
Mouse pad	P	53	0.26 x 0.22	0.1 ea	Exposed from upper and side faces
Computer table	W	53	~1.47 x 0.4 x 0.02 (x2) ~ 0.485 x 0.64 x 0.03 (x2) ~ 0.985 x 0.895 x 0.03 (x2) ~ 0.605 x 0.65 x 0.02 (x2) ~ 0.02 x 0.4 x 1.47 (x2)	50 ea	All faces except the part underneath
Blinds	P	9	0.98 x 1.855	2 ea	Exposed from upper and side faces
		1	1.23 x 2.75	3 ea	Exposed from upper and side faces

** N/A ~ steel materials are considered to be low fuel load in fire. Thus, surfaces are not involved in the fire.*
W = Wood, P = Plastic, S = Steel, E = Electrical, G = Glass.

Table 8.2.4.1: Summary descriptions of each fuel load in Civil Engineering computer lab.

Besides the thinner portion of the cellulosic materials, most of the non-cellulosic materials will have a shorter burning period than the thicker portion of the cellulosic materials.

Figure 8.2.4.1 shows the layout of Civil Engineering computer lab.

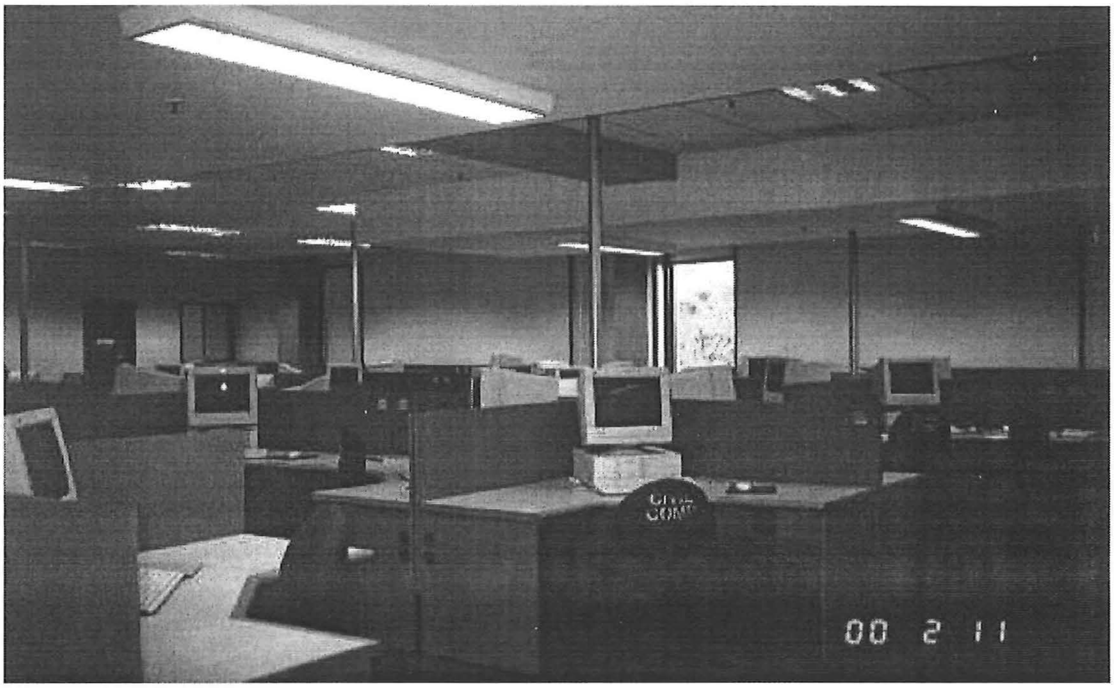


Figure 8.2.4.1: Layout of Civil Engineering computer lab.

Figure 8.2.4.2 below shows the total amount of heat release rate available inside the room. The maximum value of the heat release rate is approximately 214 MW, based on the total exposed surface area of the fuel loads during a post-flashover fire. The ventilation limit is approximately 43 MW. There is a large drop in the value of the heat release rate at the beginning of the burning duration due to the complete burning of the thinner portions of the fuel loads. After the large drop, the values of heat release rate decrease according to the burning of the thicker portions of the fuel loads inside the room. Figure below indicates more fuel being burnt beyond the ventilation limit as more surfaces of the fuel loads are being exposed to the fire. The larger the exposed surface area, the higher the value of the heat release rate.

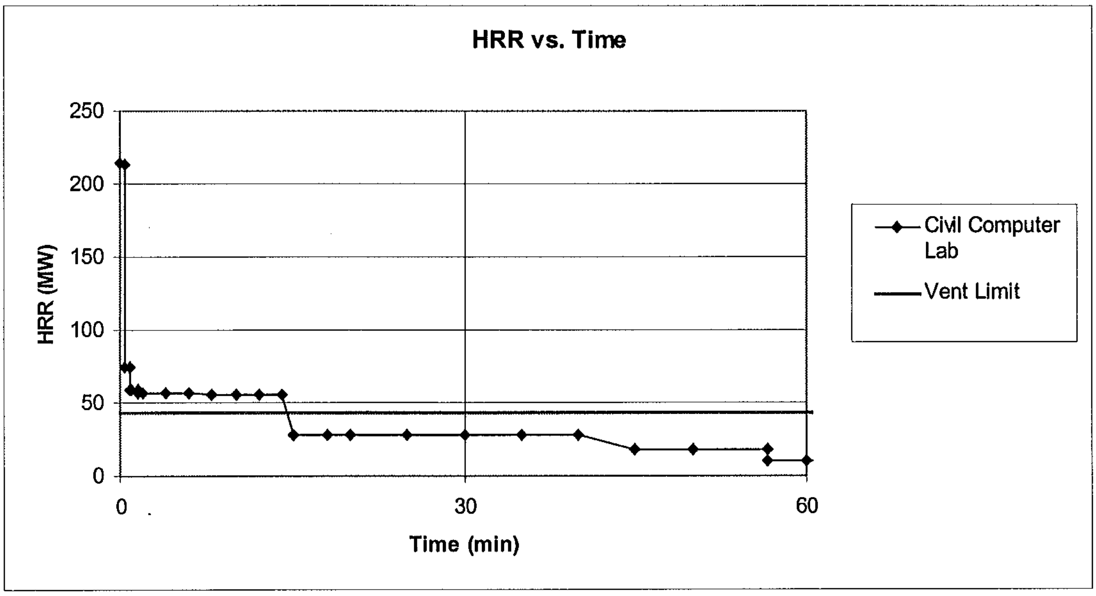


Figure 8.2.4.2:HRR vs. Time graph for fuel load inside Civil Engineering computer lab.

In describing the behaviour of the figure above, option (a) indicates that during the post-flashover fire, due to the limited air supply to support the burning, all the unburnt fuel is going to burn outside the building. This is showed by the heat release curve, which is beyond the ventilation limit, shown in Figure 8.2.4.2 above. However, in the figure, this portion of the energy release is given off by most of the burning of the thinner portion of the fuel, with their surfaces exposed to fire.

Figure 8.2.4.3 shows the concept described for option (b). As before, the amount of heat release rate beyond the ventilation limit (E1) is shifted downward, under the ventilation limit, and the original amount energy under the ventilation limit (E2) is shifted to the right side of E1.

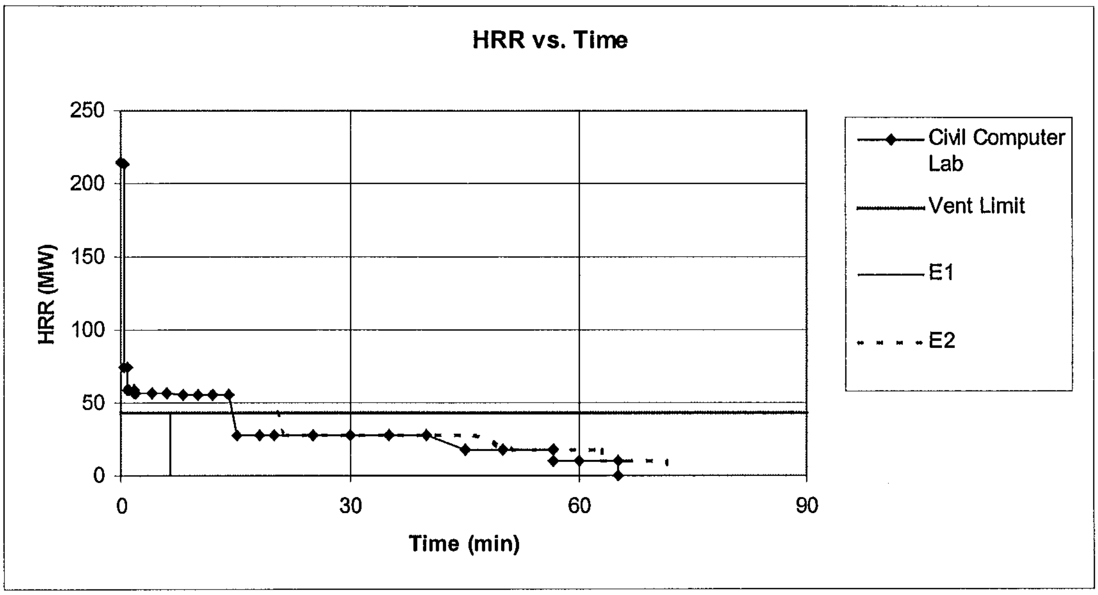


Figure 8.2.4.3:HRR vs. Time graph showing the shifting of E1 and E2 under the ventilation limit for Civil Engineering computer lab.

By shifting and dividing the original curve into E1 and E2, the heat release rate curve will shift by approximately 7 minutes. The shift is considered to be quite large. This is because before the shift, there is a high value of energy release beyond the ventilation limit due to larger exposure of the fuel surfaces. The trend of E1 and E2 shown in Figure 8.2.4.3 indicates that E1, which is nearer to the window, will be burned first before the burning of the fuel loads E2, which are further away from the window.

8.2.5 Civil Engineering Meeting Room

Again as Civil engineering computer lab, this meeting room has a large room area, limited fuel loads and large area of ventilation openings. The dimension of the room is approximately 13.5 m x 9 m, with a number of windows. It also has a door with a dimension of approximately 2 m x 2.2 m, but again it is not considered to be a source of ventilation as it opens to a corridor, which has limited air, inside the building. Furthermore, the door is considered in the closed position during the modelling.

Table 8.2.5.1 below shows the summary descriptions of each item, with their exposed surface areas carefully assessed.

Fire Load	Type	Quantity	Dimensions (m)	Mass (kg) (approx.)	Surface Area Exposed
Fixed					
Carpet	P	1	13.475 x 8.8	55 ea	Exposed from upper face
Door + frame	W	2	0.91 x 2.225 x 0.02	20 ea	Exposed from inside the compartment
Window sill	W	1	19 x 0.2 x 0.035	35 ea	Front and upper faces exposed
Moveable					
Table (I)	W +S	11	See Figure 6.8.1.2	20 ea	All faces except the part underneath the table
Plastic chair (II)	P + S	39	0.41 x 0.22	7 ea	Exposed from upper and side faces
Projector table	W + S	2	~ 1.1 x 0.52 x 0.02 ~ 0.5 x 0.5 x 0.02	20 ea	All faces except the part underneath
Projector	P + S + G	1	0.36 x 0.42	8 ea	Exposed from upper and side faces
Telephone	P + S + E	1	0.165 x 0.225	1 ea	Exposed from upper and side faces
Rubbish bin	P	1	diameter = 0.3	1 ea	Exposed from upper and side faces
Papers	W	1	0.21 x 0.1 x 0.275	2 ea	All faces except the part underneath
Curtains	P	1	13.765 x 0.43	3 ea	Exposed from front and side faces
Computer	P + S + G + E	1	0.64 x 0.4	10 ea	Exposed from upper and side faces
Bookshelf (I) ~ empty	W	2	See Figure 6.2.1.2	12 ea	All faces except back
Blocks	W	1	0.22 x 0.24 x 0.18	3 ea	All faces except back
Hollow cabinet	W	1	0.52 x 0.52 x 0.42 with thickness 0.02	5 ea	All faces except the part underneath

** N/A ~ steel materials are considered to be low fuel load in fire. Thus, surfaces are not involved in the fire.*

W = Wood, P = Plastic, S = Steel, E = Electrical, G = Glass.

Table 8.2.5.1: Summary descriptions of each fuel load in Civil Engineering meeting room.

It is found that non-cellulosic materials, such as the curtains and the thinner parts of the cellulosic materials will completed the burning first. The total duration of burning inside this compartment is determined by the thickest parts of the cellulosic materials.

Figure 8.2.5.1 shows the layout of Civil Engineering meeting room.

Figure 8.2.5.1: Layout of Civil Engineering meeting room.

Figure 8.2.5.2 below shows the total amount of heat release rate available inside the room. The maximum value of the heat release rate is approximately 85.3 MW, based on the total exposed surface area of the fuel loads during a post-flashover fire. The ventilation limit is about 8.3. There is a large drop in the value of the heat release rate at the beginning of the burning duration due to the complete burning of the thinner portions of the fuel loads, with their surface exposed to the fire. After the large drop, the values of heat release rate decrease according to the burning of the thicker portions of the fuel loads inside the room.

Although, the results showed a high value of the heat release rate inside the room, the fire load density for this room is only about 102 MJ/m^2, which is in agreement with the total number of the fuel load inside the room. This is because all the fuel surfaces are freely exposed to the fire. Consequently, this means that the larger the surface area exposed to the fire, the higher the value of the heat release rate.

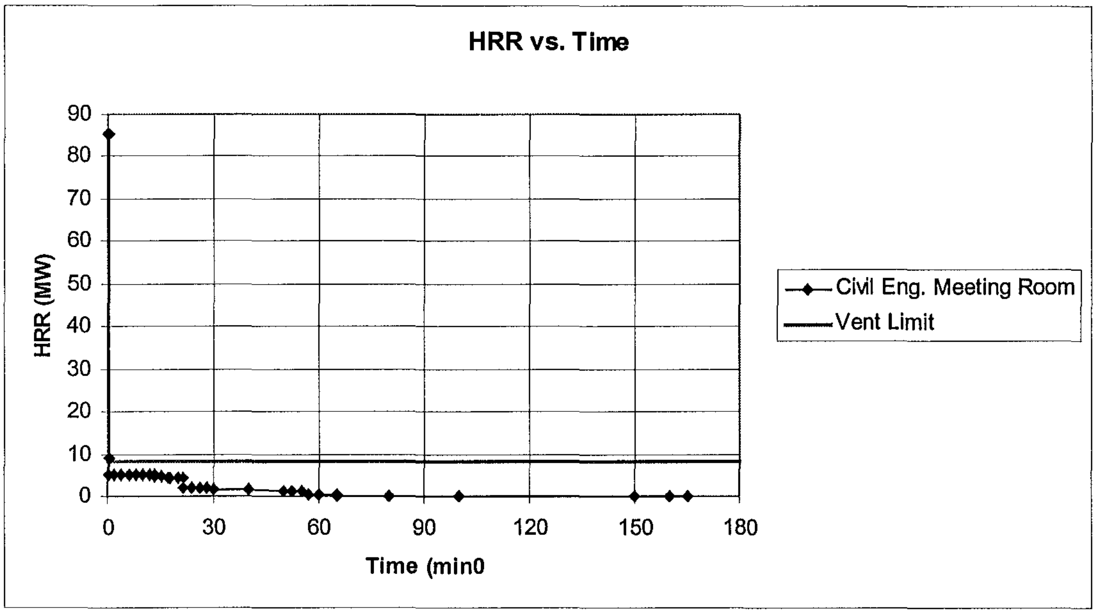


Figure 8.2.5.2:HRR vs. Time graph for fuel load inside Civil Engineering meeting room.

In order to explain the behaviour of Figure 8.2.5.2, option (a) indicates that during the post-flashover fire, due to the limited air supply to support the burning, some fuel is going to burn outside the building. This is showed by the heat release curve, which is beyond the ventilation limit, shown in the figure above. This portion of the energy release is given off by most of the burning of the thinner portion of the fuel, with their surfaces exposed to fire.

Figure 8.2.5.3 shows the concept described for option (b). As before, the amount of heat release rate beyond the ventilation limit (E1) is shifted downward, under the ventilation limit, and the original amount energy under the ventilation limit (E2) is shifted to the right side of E1.

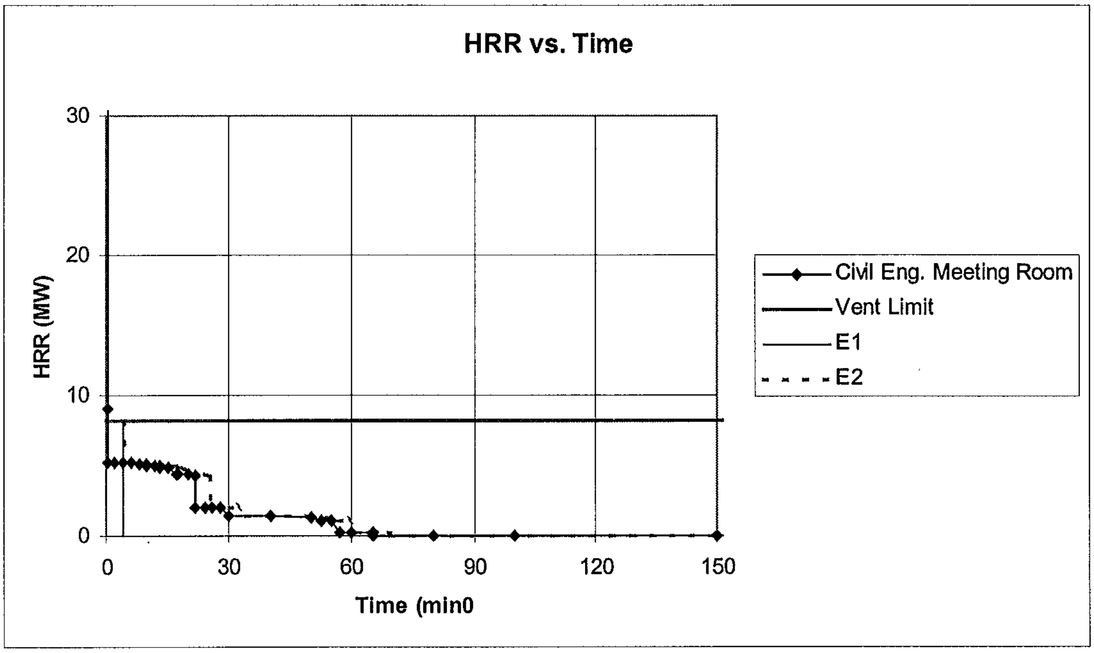


Figure 8.2.5.3:HRR vs. Time graph showing the shifting of E1 and E2 under the ventilation limit for Civil Engineering meeting room.

After the shift, the position of the heat release curve will be shifted by about 4 minutes. The trend of E1 and E2 shown in Figure 8.2.5.3 indicates that E1, which is nearer to the window, will be burned first before the burning of the fuel loads E2, which are further away from the window takes place.

8.2.6 Civil Engineering Store Room

The store room has a room dimension of 5.32 m x 2.78 m. It has one window opened to the outside air, with a dimension of 2.29m x 1.51 m. The glass on the window is assumed to be broken during the post-flashover fire. Although the room has a door with a dimension of approximately 1 m x 2.2 m, it is not considered to be a source of ventilation as it opens to a corridor which has limited air, inside the building. Furthermore, the door is considered to be closed during the fire.

The store room contains a lot of fuel load ranging from wood materials to plastic materials, which are assumed to be ignited all at once during a post-flashover fire. The exposed surface areas of each item are carefully assessed. Table 8.2.6.1 below shows the summary descriptions of each item.

Fire Load	Type	Quantity	Dimensions (m)	Mass (kg) (approx.)	Surface Area Exposed
Fixed					
Carpet	P	1	2.78 x 5.32	25 ea	Exposed from upper face
Door + frame	W	1	0.91 x 2.225 x 0.02	20 ea	Exposed from inside the compartment
Window sill	W	1	2.29 x 0.2 x 0.032	8 ea	Front and upper faces exposed
Notice board	W	1	0.9 x 0.6 x 0.018	5 ea	All faces except back
Moveable					
Bookshelf ~ overall 80% full (larger version of Bookshelf (II))	W	1	See Figure 6.2.2.2	100 ea	All faces except back
Bookshelf (III) ~ 75% full	W	1	See Figure 6.2.3.2	65 ea	All faces except back
Box of books and papers	W	40	0.38 x 0.52 x 0.21	15 ea	All faces except the part underneath
Bookshelf (I) ~ empty	W	1	See Figure 6.2.1.2	12 ea	All faces except back
Cupboard (I) ~ empty	W	2	See Figure 6.5.1.2	30 ea	All faces except back
Desk (II) ~ empty	W	1	See Figure 6.6.2.2	26 ea	All faces except back
Table (III)	W +S	1	0.67 x 0.52 x 0.04	15 ea	All faces except the part underneath the table
Picture frames	W	2	0.5 x 0.66 x 0.6	25 ea	All faces except back
Telephone	P + S + E	3	0.165 x 0.225	1 ea	Exposed from upper and side faces
Cupboard with drawers (empty)	W	2	1.21 x 0.99 x 0.65 with thickness 0.03	45 ea	All faces except back
Blinds	P	1	2.29 x 1.505	3.1 ea	Exposed from upper and side faces
Chair	W + S + P	1	0.6 x 0.565	12 ea	Exposed from upper and side faces
Others	P	1	0.15 x 0.2	2 ea	Exposed from upper and side faces
Others	W	1	0.9 x 0.7 x 0.03	3 ea	All faces except the part underneath
Papers	W	1	0.45 x 0.33 x 0.04	3 ea	Exposed from upper and side faces
		1	0.21 x 0.1 x 0.275	~ 2.6 ea	Exposed from upper and side faces
		1	0.9 x 0.6 x 0.0001	~ 0.1 ea	Exposed from upper and side faces

** N/A ~ steel materials are considered to be low fuel load in fire. Thus, surfaces are not involved in the fire.*

W = Wood, P = Plastic, S = Steel, E = Electrical, G = Glass.

Table 8.2.6.1: Summary descriptions of each fuel load in Civil Engineering store room.

All the thinner portion of cellulosic materials, and most of the non-cellulosic materials will have a shorter burning period than the thicker portion of the cellulosic materials. In other words, thermoplastic materials will burn out before wood materials.

Figure 8.2.6.1 shows the layout of Civil Engineering store room.

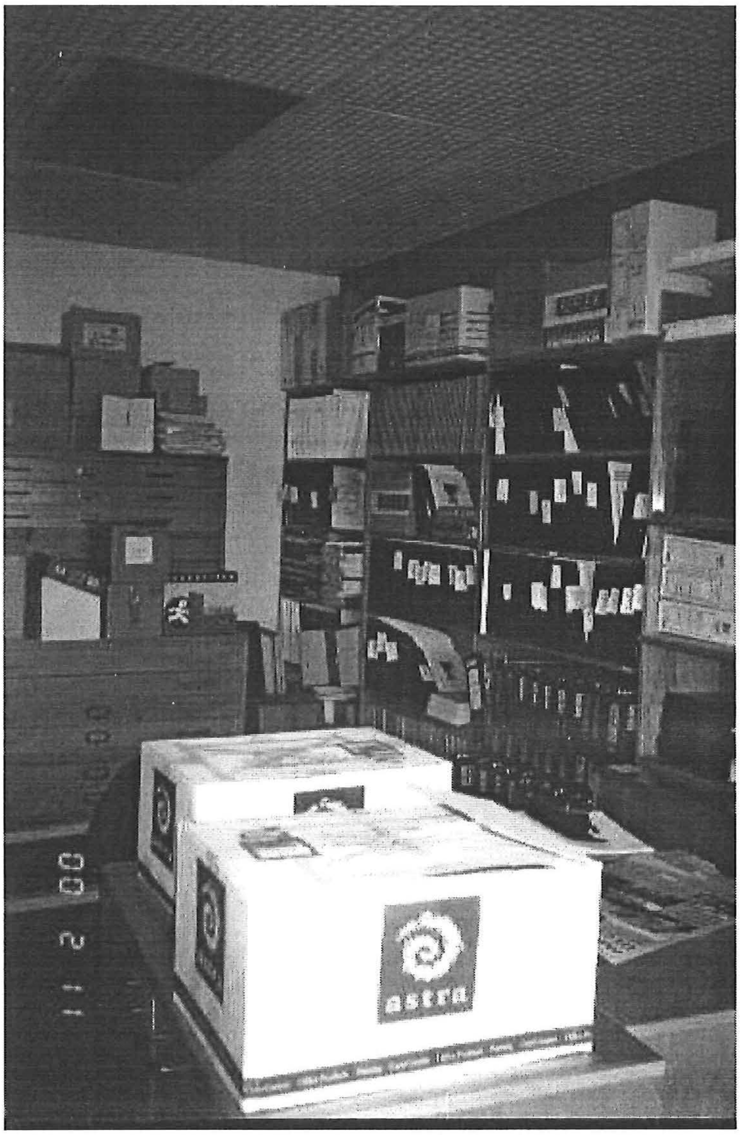


Figure 8.2.6.1: Layout of Civil Engineering store room.

Figure 8.2.6.2 below shows the total amount of heat release rate available inside the store room.. The maximum value of the heat release rate is approximately 18.6 MW, based on the total exposed surface area of the fuel loads during a post-flashover fire. The ventilation limit is approximately 6.5 MW. There is a large drop in the value of the heat release rate at the beginning of the burning duration due to the complete burning of the thinner portions of the fuel loads, with large surface area exposed to the fire initially. After the large drop, the values of heat release rate decrease according to the burning of the thicker portions of the fuel loads inside the office, which in a way have less exposed surface area to the fire.

The fire load density for this store room is about 2400 MJ/m^2. Although this value shows that the amount of the fuel load inside the store room is very high, one would expect to see a higher portion of heat release curve predicted beyond the ventilation limit. This is due to the quantities of the burning fuel exceeding the available ventilation which is needed to support the burning.

However, as seen in Figure 8.2.6.2, the result obtained is not as expected. This is because the outcome of the value of the heat release rate is based on the total amount of the exposed surface areas of the fuel loads to the fire, and not the total amount of the fuel loads (in kg) stored inside the store room. Consequently, this means that the lesser the surface area exposed to the fire, the lower the value of the heat release rate.

As most of the furniture inside the room was full (ie. bookshelf full of books), simple shape of the fuel was adopted in predicting the surface area exposed for each complicated item. This reduced the possibility of more surfaces being exposed to the fire, which in term reduced the value of the heat release rate. This explanation can be supported by the data presented for single items in Chapter 6 (ie. see section 6.2).

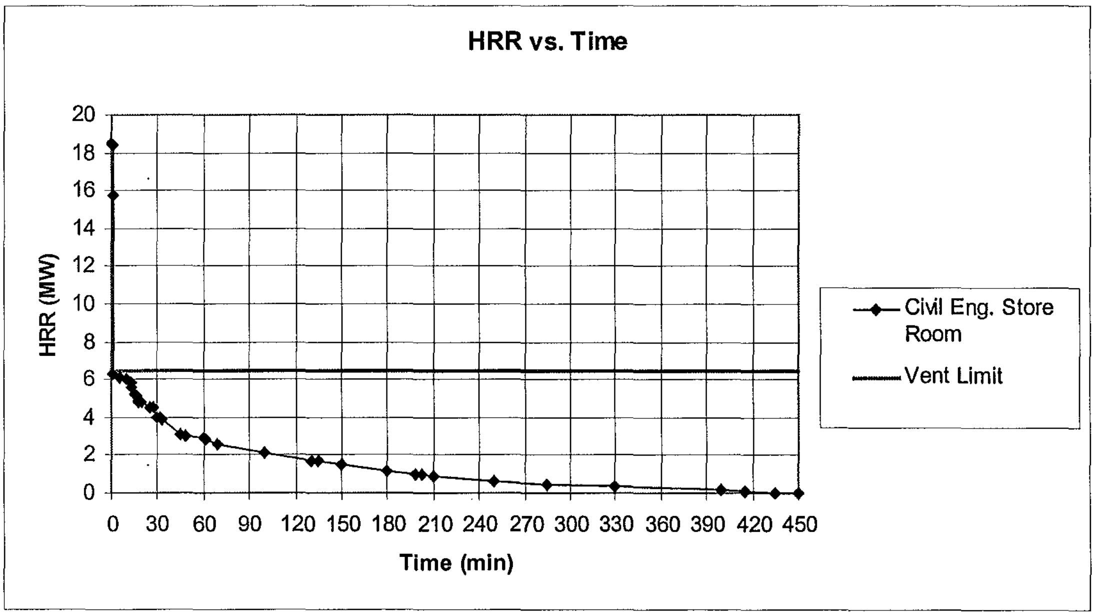


Figure 8.2.6.2:HRR vs. Time graph for fuel load inside Civil Engineering store room.

The behaviour of Figure 8.2.6.2, for option (a), indicates that during the post-flashover fire, due to the limited air supply to support the burning, some fuel is going to burn outside the building. This is showed by the heat release curve, which is beyond the ventilation limit. This portion of the energy release is mostly given off by the burning of the thinner portion of the fuel.

Figure 8.2.6.3 shows the concept described for option (b). As before, the amount of heat release rate beyond the ventilation limit (E1) is shifted downward, under the ventilation limit, and the original amount energy under the ventilation limit (E2) is shifted to the right side of E1.

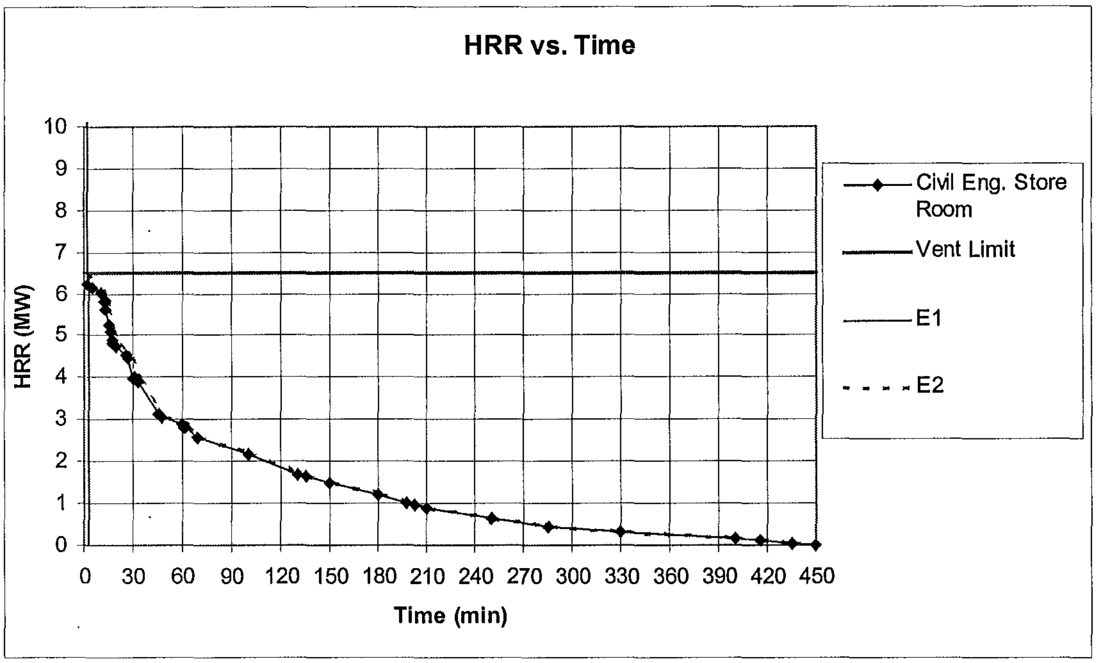


Figure 8.2.6.3:HRR vs. Time graph showing the shifting of E1 and E2 under the ventilation limit for Civil Engineering store room.

By shifting and dividing the original curve into E1 and E2, the heat release rate curve will shift by only 3 minutes. The trend of E1 and E2 shown in Figure 8.2.6.3 indicates the concept that E1, which is nearer to the window, will be burned first before the burning of the fuel loads E2, which are further away from the window.

8.3 Flat (Bedroom)

8.3.1 Bedroom (I)

Bedroom (I) has a room dimension of 3.54 m x 2.51 m. It has two large windows opened to the outside air with a dimension of 0.92 m x 1.96 m each, in which the glass is assumed to be broken during the post-flashover fire. It has a door with dimensions of approximately 0.87 m x 2 m, but the door is considered to be closed during a fire.

The fuel loads inside the bedroom is not as high as a normal typical bedroom. Table 8.3.1.1 below shows the summary descriptions of each item with the exposed surface areas of each item carefully assessed.

Fire Load	Type	Quantity	Dimensions (m)	Mass (kg) (approx.)	Surface Area Exposed
Fixed					
Built-in cupboard + frame	W	1	0.02 x 1.87 x 1.2	10 ea	Front and side faces only
Door + frame	W	1	0.015 x 0.865 x 2.04	18 ea	Exposed from inside the compartment
Window sill	W	2	0.08 x 0.07 x 1.96	8 ea	Front and upper faces exposed
Moveable					
Contents inside cupboard	P	1	1.2 x 0.52	20 ea	Exposed from upper and side faces
Bed	P + W	1	1.88 x 0.9	90 ea	Exposed from upper and side faces
Pillow	P	2	0.35 x 0.64	1.5 ea	Exposed from upper and side faces
Heater (plastic part only)	P	1	0.12 x 0.76	1 ea	Exposed from upper and side faces
Small cabinet ~ full	W	1	See Figure 6.5.2.2	10 ea	All faces except back
Radio	P + E	1	0.49 x 0.2	4 ea	Exposed from upper and side faces
Desk (II) ~ full	W	1	See Figure 6.6.2.2	26 ea	All faces except back
Chair	P	1	0.08 x 0.5	2 ea	Exposed from upper and side faces
Rug	P	1	0.61 x 1.28	2 ea	Exposed from upper and side faces
Curtain	P	1	0.92 x 1.96	2 ea	Exposed from front and side faces
Other plastic things	P	1	0.925 x 0.425	5 ea	Exposed from upper and side faces
Books and papers	W	2	0.34 x 0.48 x 0.26	12 ea	All faces except the part underneath

** N/A ~ steel materials are considered to be low fuel load in fire. Thus, surfaces are not involved in the fire.*
W = Wood, P = Plastic, S = Steel, E = Electrical, G = Glass.

Table 8.3.1.1: Summary descriptions of each fuel load in Bedroom (I).

During the modelling for each item available inside the bedroom, besides the thinner portion of cellulosic materials, such as thin, loose paper sheets, it is found that almost all the non-cellulosic materials have a shorter burning period than the thicker portion of the cellulosic materials.

Figure 8.3.1.1 shows the layout of Bedroom (I).

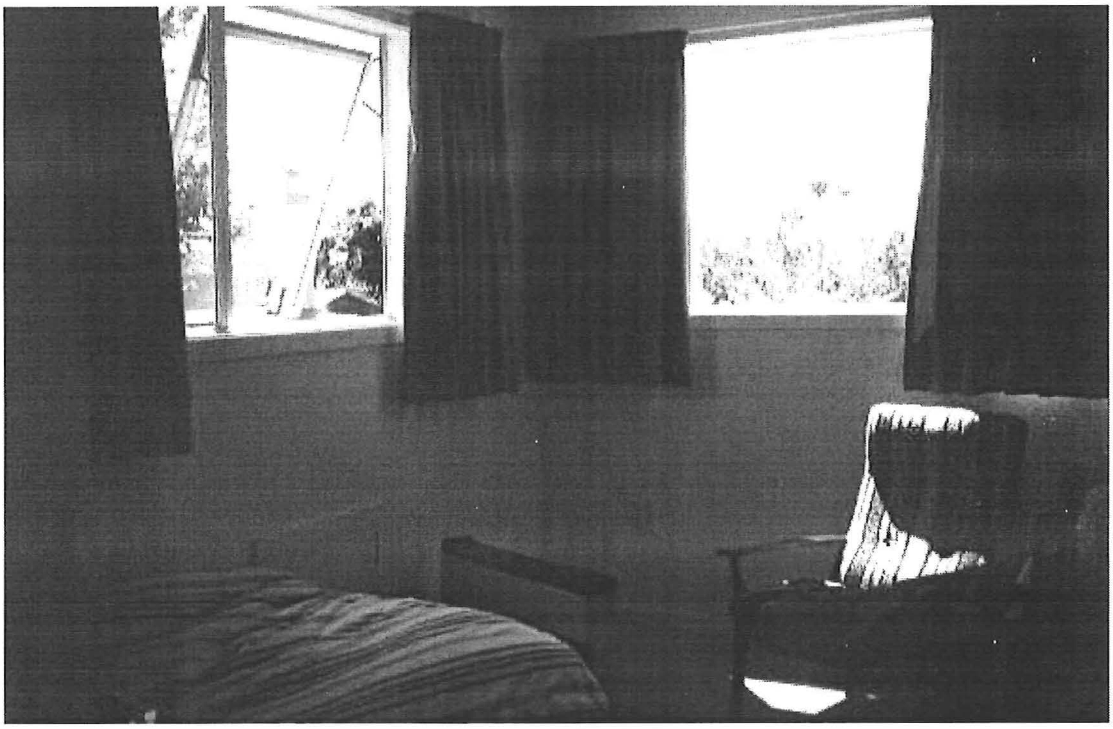


Figure 8.3.1.1: Layout of Bedroom (I).

Figure 8.3.1.2 below shows the total amount of heat release rate available inside the bedroom. The maximum value of the heat release rate is approximately 4.6 MW, based on the exposed surface area of the fuel loads during a post-flashover fire. The ventilation limit is approximately 5.3 MW. Each drop in the value of the heat release rate means the complete burning of the thinner portions of the fuel loads. The duration of the burning is determined by the thickest part of the fuel load.

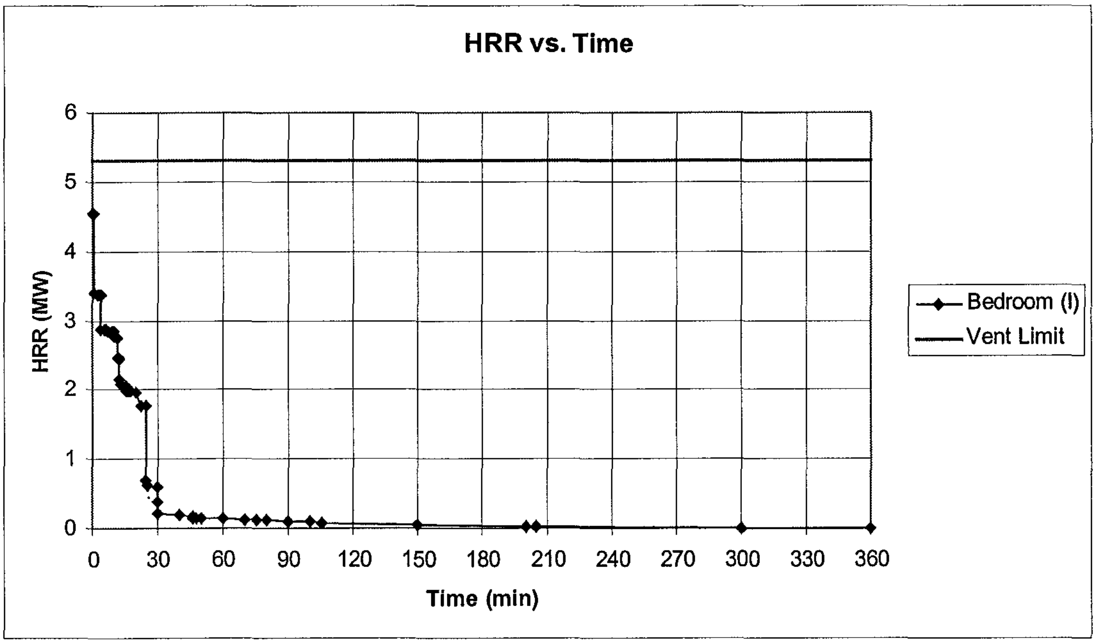


Figure 8.3.1.2: HRR vs. Time graph for fuel load inside Bedroom (I).

From Figure 8.3.1.2, one could see that the energy release of the fuel load inside the bedroom is under the ventilation limit. This is due to the large air supply to the room. Besides that, the amount of the fuel loads are not as much as expected, which in turn reduce the possible amount of surface areas exposed to the fire.

8.3.2 Bedroom (II)

Bedroom (II) has a room dimension of 2.39 m x 3.3 m. It has a window opened to the outside air with a dimension of 0.92 m x 2.1 m. The glass on the window is assumed to be broken during the post-flashover fire. Although the bedroom has a door with a dimension of approximately 0.87 m x 2 m, it is not considered to be a source of ventilation as it opens to a corridor, which has limited air. Furthermore, the door is considered to be in the closed position during the modelling.

The bedroom contains all sorts of fuel load ranging from wood materials to plastic materials, which are assumed to be ignited all at once during a post-flashover fire. The exposed surface areas of each item are carefully assessed. Table 8.3.2.1 below shows the summary descriptions of each item.

Fire Load	Type	Quantity	Dimensions (m)	Mass (kg) (approx.)	Surface Area Exposed
Fixed					
Door + frame	W	1	0.015 x 0.865 x 2.04	18 ea	Exposed from inside the compartment
Window sill	W	1	0.08 x 0.07 x 2.085	8 ea	Front and upper faces exposed
Moveable					
Desk (II) ~ full	W	1	See Figure 6.6.2.2	26 ea	All faces except back
Plastic chair (II)	P + S	1	0.41 x 0.22	7 ea	Exposed from upper and side faces
Small bookshelf	W	1	0.26 x 0.505 x 0.91	15 ea	All faces except back
Bed	P + W + S	1	1.88 x 0.9	55 ea	Exposed from upper and side faces
Pillow	P	1	0.35 x 0.64	1.5 ea	Exposed from upper and side faces
Bed's legs	W	4	diameter = 0.06	1 ea	All faces
Rug	P	1	0.61 x 1.28	2 ea	Exposed from upper and side faces
Radio	P + E	1	0.49 x 0.2	4 ea	Exposed from upper and side faces
Dustbin	P	1	0.23 x 0.17	0.5 ea	Exposed from upper and side faces
Plastic container	P	1	0.35 x 0.41	4 ea	Exposed from upper and side faces
Curtain	P	1	2.085 x 0.92	2 ea	Exposed from front and side faces
Other plastic things	P	1	0.63 x 0.3	2 ea	Exposed from upper and side faces
Others	W	1	0.63 x 0.3 x 0.03	2.5 ea	All faces except the part underneath
Box of books and papers	W	6	0.34 x 0.48 x 0.26	15 ea	All faces except the part underneath

** N/A ~ steel materials are considered to be low fuel load in fire. Thus, surfaces are not involved in the fire.*
W = Wood, P = Plastic, S = Steel, E = Electrical, G = Glass.

Table 8.3.2.1: Summary descriptions of each fuel load in Bedroom (II).

The thinner portion of cellulosic materials and most of the non-cellulosic materials inside the bedroom will burn out before the thicker portion of the cellulosic materials.

Figure 8.3.2.1 shows the layout of Bedroom (II).

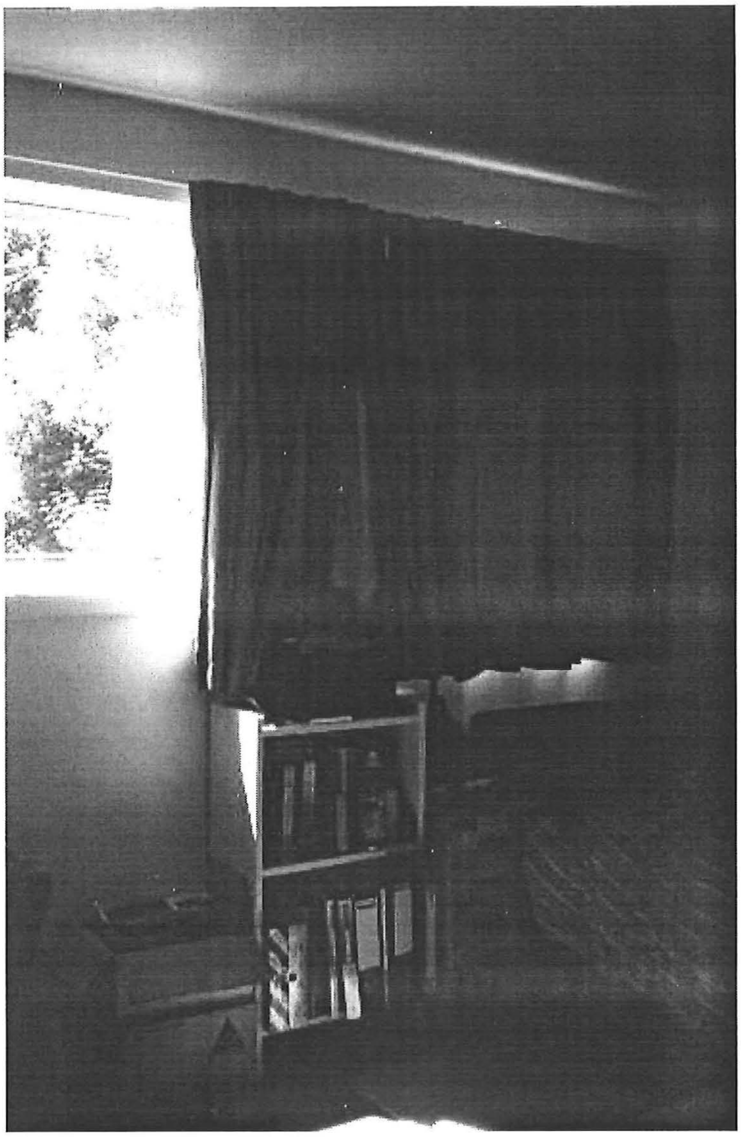


Figure 8.3.2.1: Layout of Bedroom (II).

Figure 8.3.2.2 below shows the total amount of heat release rate available inside the bedroom. The maximum value of the heat release rate is approximately 4.2 MW, based on the total exposed surface area of the fuel loads during a post-flashover fire. The ventilation limit is about 2.8 MW. Each drop in the value of the heat release rate means the complete burning of the thinner portions of the fuel loads. The duration of the burning is determined by the thickest part of the fuel load.

The fire load density for this bedroom is approximately 700 MJ/m^2. Although this value shows that the amount of the fuel load inside the bedroom is quite high, one would expect to see a higher portion of heat release curve predicted beyond the ventilation limit. This is due to the quantities of the burning fuel exceeding the available ventilation, which is needed to support the burning.

However, as seen in Figure 8.3.2.2, the result obtained is not as expected. This is because the outcome of the value of the heat release rate is based on the total amount of the exposed surface areas of the fuel loads to the fire, and not the total amount of the fuel loads (in kg) stored inside the bedroom, as conducted by previous surveys. Consequently, this means that the lesser the surface area exposed to the fire, the lower the value of the heat release rate.

As most of the furniture inside the bedroom was full or partially full (ie. bookshelf full of books), simple shape of the fuel was adopted in predicting the surface area exposed for each complicated item. This reduced the possibility of more surfaces being exposed to the fire, which in turn reduced the value of the heat release rate. This explanation can be supported by the data presented for single items in Chapter 6 (ie. see section 6.2).

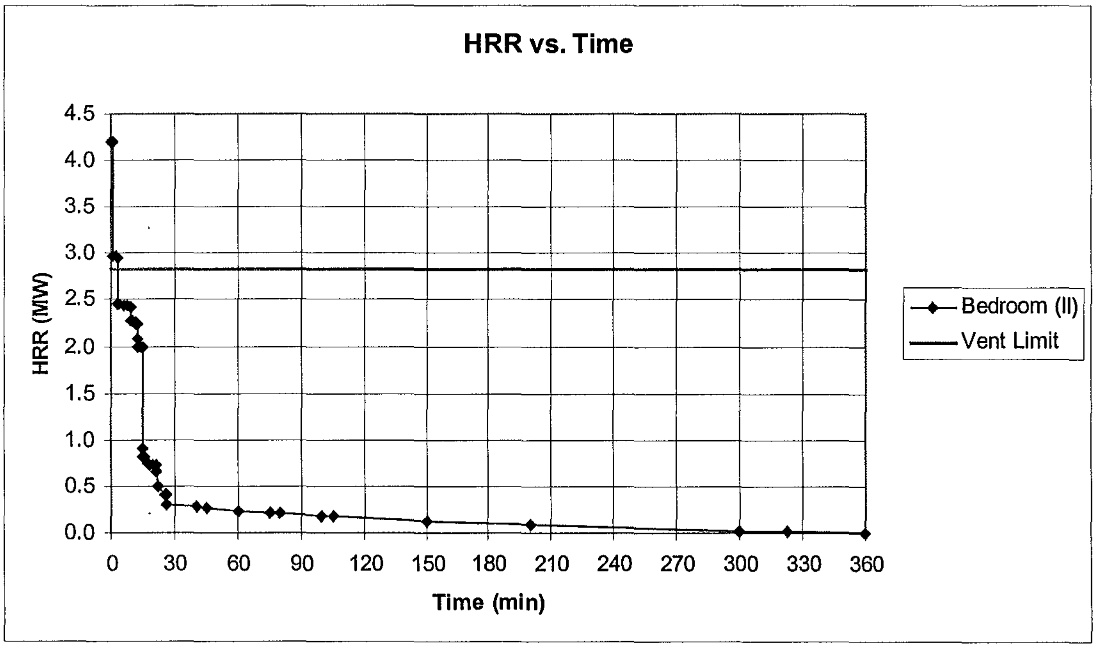


Figure 8.3.2.2: HRR vs. Time graph for fuel load inside Bedroom (II).

The behaviour of the figure above, for option (a), indicates that during the post-flashover fire, due to the limited air supply to support the burning, all the unburnt fuel is going to burn outside the room in the open air. This is showed by the heat release curve, which is beyond the ventilation limit. This portion of the energy release is given off mostly by the burning of the thinner portion of the fuel.

Figure 8.3.2.3 shows the concept described for option (b). As before, the amount of heat release rate beyond the ventilation limit (E1) is shifted downward, under the ventilation limit, and the original amount energy under the ventilation limit (E2) is shifted to the right side of E1.

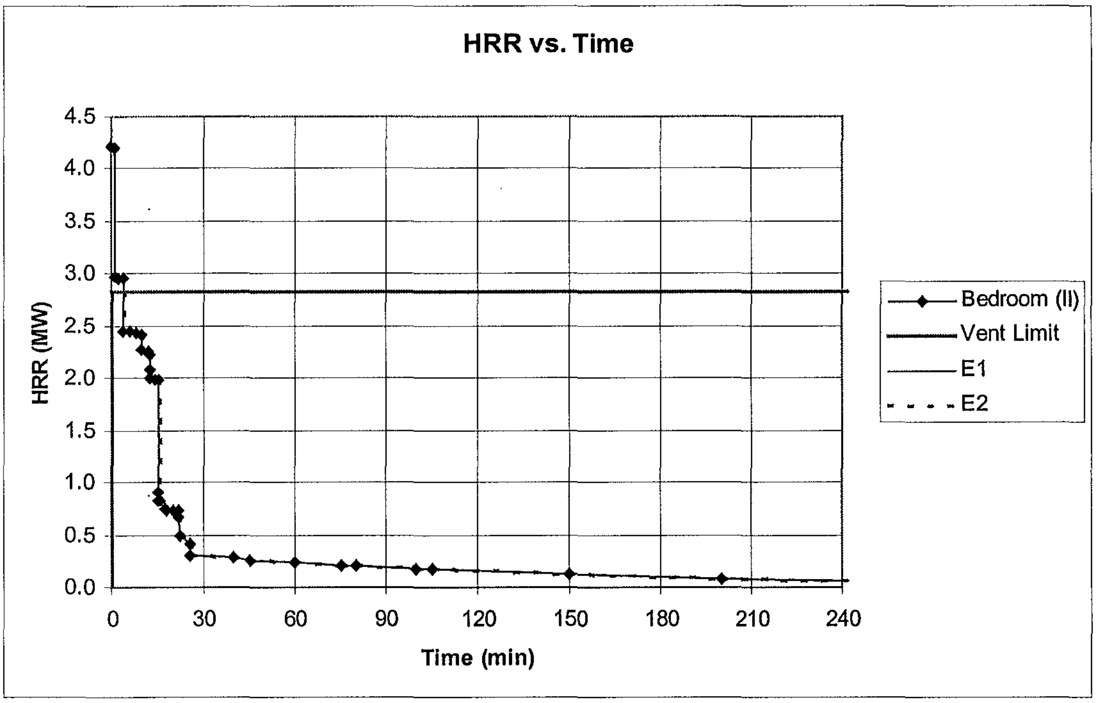


Figure 8.3.2.3:HRR vs. Time graph showing the shifting of E1 and E2 under the ventilation limit for Bedroom (II).

By shifting and dividing the original curve into E1 and E2, the heat release rate curve will shift by only 1 minutes. The trend of E1 and E2 shown in Figure 8.3.2.3 indicates that E1, which represent the fuel loads nearer to the window, will be burned first before the burning of the fuel loads E2, which are further away from the window takes place.

8.3.3 Bedroom (III)

Bedroom (III) has a room dimension of approximately 4.06 m x 3.3 m. It has a ventilation opening, which is considered to be quite large, with a dimension of 2.61 m x 1.4 m. The glass on the opening to the outside air is assumed to be broken during the post-flashover fire. Although the bedroom has a door with a dimension of approximately 0.9 m x 2.1 m, it is not considered to be a source of ventilation as it opens to the living room, which has limited air, inside the flat. Furthermore, the door is considered to be in the closed position during the modelling.

The bedroom contains all sorts of fuel load ranging from wood materials to plastic materials, which are assumed to be ignited all at once during a post-flashover fire. The exposed surface areas of each item are carefully assessed. Table 8.3.3.1 below shows the summary descriptions of each item.

Fire Load	Type	Quantity	Dimensions (m)	Mass (kg) (approx.)	Surface Area Exposed
Fixed					
Built-in cupboard + frame	W	1	1.87 x 1.2 x 0.02	10 ea	Front and side faces only
Door + frame	W	1	0.02 x 0.895 x 2.063	18 ea	Exposed from inside the compartment
Carpet	P	1	4.06 x 3.33	30 ea	Exposed from upper face
Moveable					
Contents inside cupboard	P	1	1.2 x 0.52	30 ea	Exposed from upper and side faces
Bed	P + W + S	2	1.88 x 0.9	90 ea	Exposed from upper and side faces
Pillow	P	2	0.35 x 0.64	1.5 ea	Exposed from upper and side faces
Bed's legs	W	8	diameter = 0.07	1 ea	All faces
Heater	P +S + E	1	0.75 x 0.275	2	Exposed from upper and side faces
Radio	P + E	1	0.49 x 0.2	4 ea	Exposed from upper and side faces
Contents in rack	W	3	0.38 x 0.23 x 0.085	3 ea	All faces except the underneath face
Luggage	P	2	0.25 x 0.71 x 0.49	10 ea	Exposed from upper and side faces
Desk (II) ~ full	W	1	See Figure 6.6.2.2	26 ea	All faces except back
Desk (I) ~ full	W	1	See Figure 6.6.1.2	30 ea	All faces except back
Chair	P + S + W	2	0.465 x 0.43	7 ea	Exposed from upper and side faces
Computer + printer	P + S + G + E	1	1.1 x 0.5	14 ea	Exposed from upper and side faces
Dustbin	P	1	0.23 x 0.17	0.5 ea	Exposed from upper and side faces
Curtain	P	1	2.61 x 1.4	2 ea	Exposed from front and side faces
Telephone	P + S + E	1	0.075 x 0.23	1 ea	Exposed from upper and side faces
Other plastic things	P	1	0.3 x 0.3	2 ea	Exposed from upper and side faces
Soft toys	P	1	0.4 x 0.25	2 ea	Exposed from upper and side faces
Papers	W	1	0.9 x 0.3 x 0.06	7.5 ea	All faces except back
		2	0.84 x 0.6 x 0.0001	0.1 ea	All faces except back
		3	0.51 x 0.365 x 0.0001	0.1 ea	All faces except back
		2	0215 x 0.3 x 0.0001	0.1 ea	All faces except back
Box of books and papers	W	2	0.605 x 0.38 x 0.74	15 ea	All faces except the part underneath

** N/A ~ steel materials are considered to be low fuel load in fire. Thus, surfaces are not involved in the fire.*

W = Wood, P = Plastic, S = Steel, E = Electrical, G = Glass.

Table 8.3.3.1: Summary descriptions of each fuel load in Bedroom (III).

During the modelling for each item available inside the bedroom, it is found that besides the thinner portion of cellulosic materials, such as thin, loose paper sheets, almost all the non-cellulosic materials have a shorter burning period than the thicker portion of the cellulosic materials. In other words, thermoplastic materials will burn out before wood materials.

Figure 8.3.3.1 shows the layout of Bedroom (III).

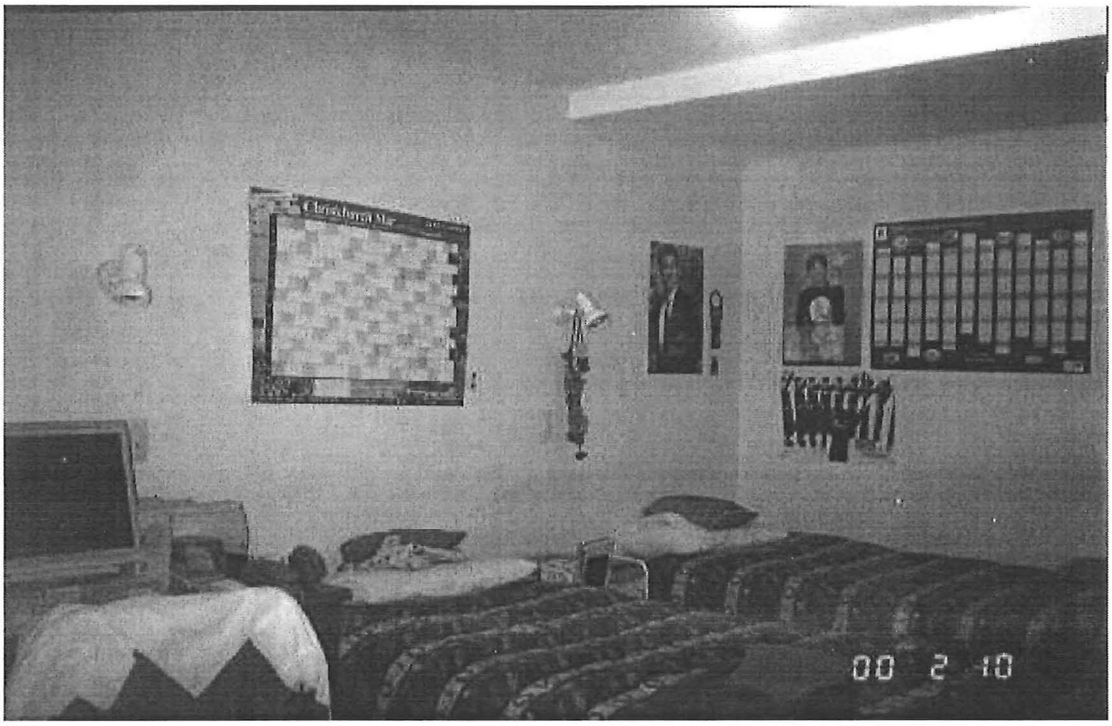


Figure 8.3.3.1: Layout of Bedroom (III).

Figure 8.3.3.2 below shows the total amount of heat release rate available inside the bedroom. The maximum value of the heat release rate is approximately 16.2 MW, based on the total exposed surface area of the fuel loads during a post-flashover fire. The ventilation limit is approximately about 6.6 MW. There is a large drop in the value of the heat release rate at the beginning of the burning duration due to the complete burning of the thinner portions of the fuel loads. The high value of the heat release rate is due to the large exposed surface areas of a certain fuel load, such as the carpet at the beginning of the fire. After the large drop, the values of heat release rate decrease according to the burning of the thicker portions of the fuel loads inside the bedroom.

The fire load density for this bedroom is approximately 850 MJ/m^2. Although this value shows that the amount of the fuel load inside the bedroom is very high, one would expected to see higher portion of heat release curve predicted beyond the ventilation limit. This is due to the quantities of the burning fuel exceeding the available ventilation, which is needed to support the burning.

However, as seen in Figure 8.3.3.2, the result obtained is not as expected. This is because the outcome of the value of the heat release rate is based on the total amount of the exposed surface areas of the fuel loads to the fire, and not the total amount of the fuel loads (in kg) stored inside the bedroom. As most of the furniture inside the bedroom is stacked closely together, this reduced the possibility of more surfaces of each fuel being exposed to the fire, which in turn reduced the value of the heat release rate.

Therefore, this means that the lesser the surface area exposed to the fire, the lower the value of the heat release rate.

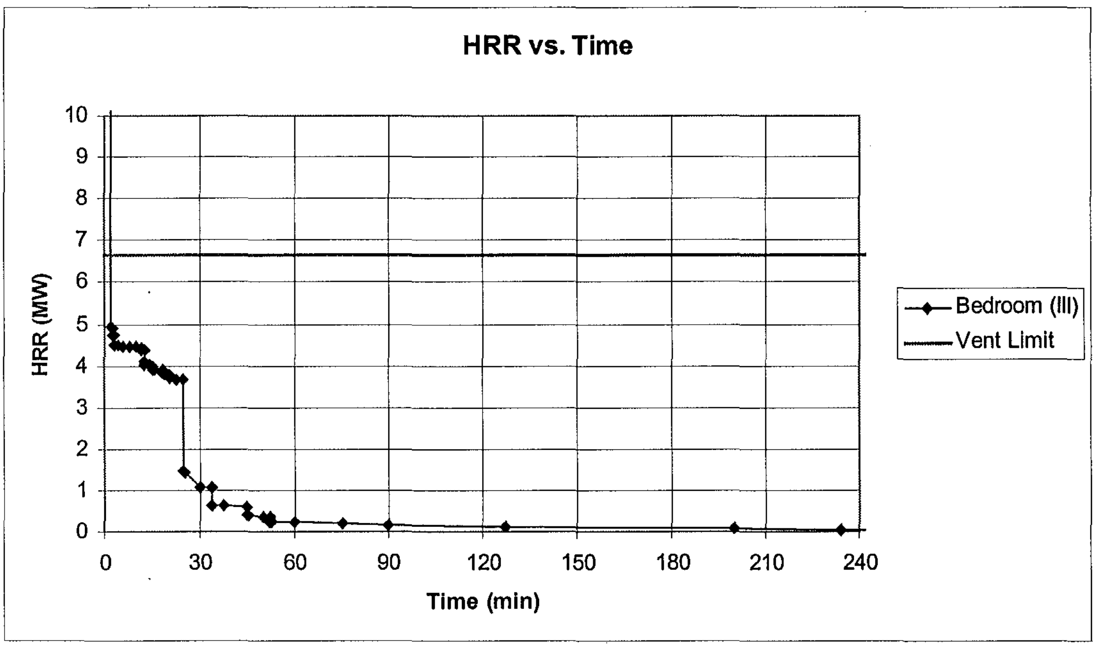


Figure 8.3.3.2: HRR vs. Time graph for fuel load inside Bedroom (III).

In order to explain the behaviour of the figure above, option (a) indicates that during the post-flashover fire, due to the limited air supply to support the burning, the unburnt fuel is going to burn outside the room with flame coming out from the window. This is showed by the heat release curve, which is beyond the ventilation limit. This portion of the energy release is given off by most of the burning of the thinner portion of the fuel, with high fuel surfaces exposed to the fire initially.

Figure 8.3.3.3 shows the concept described for option (b). As before, the amount of heat release rate beyond the ventilation limit (E1) is shifted downward, under the ventilation limit, and the original amount energy under the ventilation limit (E2) is shifted to the right side of E1.

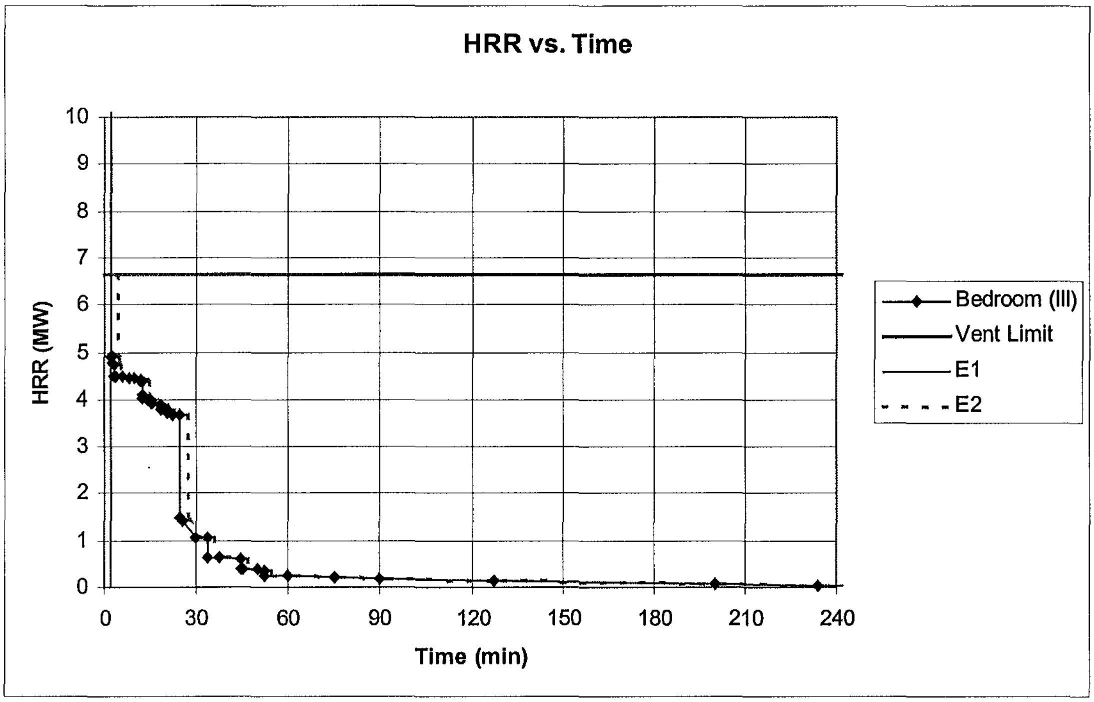


Figure 8.3.3.3:HRR vs. Time graph showing the shifting of E1 and E2 under the ventilation limit for Bedroom (III).

By shifting and dividing the original curve into E1 and E2, the heat release rate curve will shift by only 3 minutes. The trend of E1 and E2 shown in Figure 8.3.3.3 indicates that E1, which represents the fuel nearer to the window, will be burned first before the burning of the fuel loads E2, which are further away from the window takes place.

8.3.4 Bedroom (IV)

Bedroom (IV) has a room dimension of approximately 2.84 m x 2.34 m, with a large ventilation opening of approximately 1.75 m x 2.1 m. The glass on the opening is assumed to be broken during the post-flashover fire. Although the bedroom has a door with a dimension of approximately 0.76 m x 2 m, it is not considered to be a source of ventilation as it opens to the living room, which has limited air, inside the flat. Besides that, the door is considered to be in the closed position during the modelling.

The bedroom contains all sorts of fuel load ranging from wood materials to plastic materials, which are assumed to be ignited all at once during a post-flashover fire. Besides the mass and the dimensions, the exposed surface areas of each item are carefully assessed. Table 8.3.4.1 below shows the summary descriptions of each item.

Fire Load	Type	Quantity	Dimensions (m)	Mass (kg) (approx.)	Surface Area Exposed
Fixed					
Built-in cupboard + frame	W	1	0.755 x 0.02 x 2.025	10 ea	Front and side faces only
Door + frame	W	1	0.905 x 0.02 x 2.025	18 ea	Exposed from inside the compartment
Carpet	P	1	2.84 x 2.34	15 ea	Exposed from upper face
Built-in overhead compartment	W	1	0.8 x 0.24 x 0.46	5 ea	Front and lower parts only
Built-in drawers	W	1	0.8 x 0.16 x 0.46	10 ea	Exposed from upper and front faces
Moveable					
Desk ~ full	W + S	1	0.15 x 0.44 x 0.56	20 ea	All faces except back
Box of books and papers	W	3	0.34 x 0.5 x 0.28	15 ea	All faces except the part underneath
Drawing board	W	1	0.405 x 0.605 x 0.015	3 ea	All faces except the part underneath
Bed	P + W + S	1	1.91 x 0.92	55 ea	Exposed from upper and side faces
Pillow	P	2	0.35 x 0.64	1.5 ea	Exposed from upper and side faces
Bed's legs	W	4	diameter = 0.06	1 ea	All faces
Other plastic things	P	1	0.14 x 0.8	3 ea	Exposed from upper and side faces
Curtain	P	1	2.23 x 2	2 ea	Exposed from front and side faces
Contents inside cupboard	P	1	0.755 x 0.5	20 ea	Exposed from upper and side faces
Contents in built-in overhead compartment	W	1	0.4 x 0.5 x 0.45	6 ea	All faces except the underneath face

** N/A ~ steel materials are considered to be low fuel load in fire. Thus, surfaces are not involved in the fire.*
W = Wood, P = Plastic, S = Steel, E = Electrical, G = Glass.

Table 8.3.4.1: Summary descriptions of each fuel load in Bedroom (IV).

The thinner portion of cellulosic materials and most of the non-cellulosic materials will undergo a shorter burning period than the thicker portion of the cellulosic materials. Therefore, thermoplastic materials will normally be burned out before wood materials.

Figure 8.3.4.1 shows the layout of Bedroom (IV).

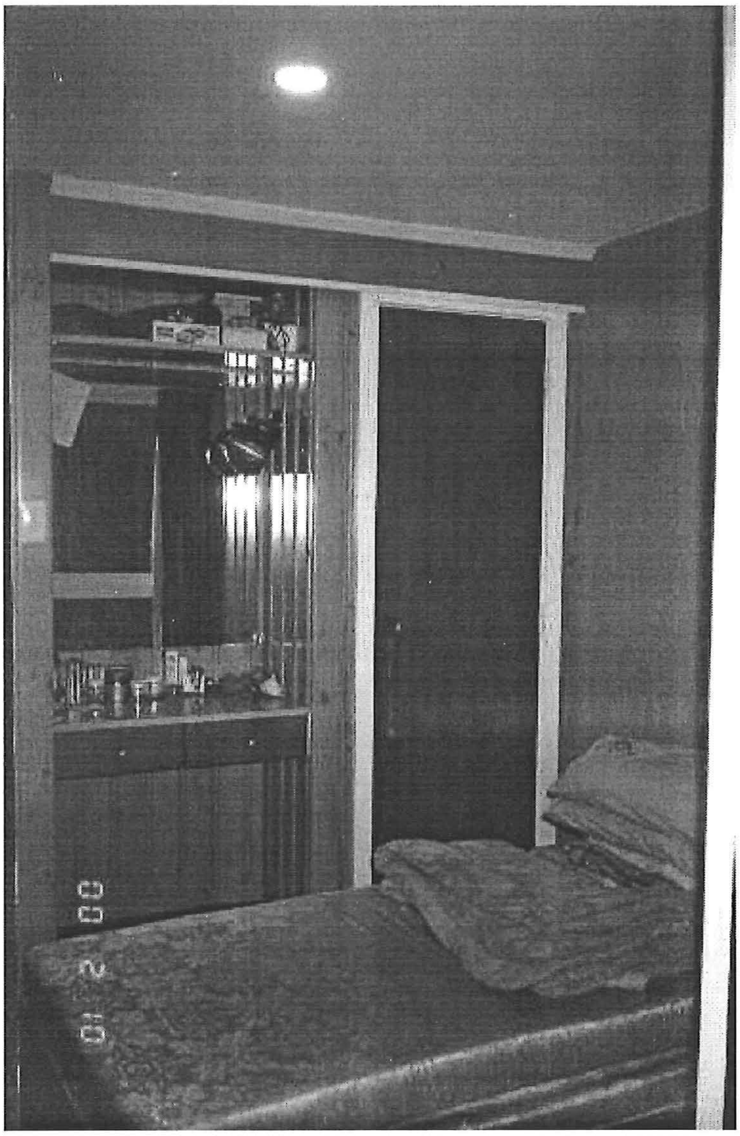


Figure 8.3.4.1: Layout of Bedroom (IV).

Figure 8.3.4.2 below shows the total amount of heat release rate available inside the bedroom. The maximum value of the heat release rate is approximately 9.6 MW, based on the total exposed surface area of the fuel loads during a post-flashover fire. The ventilation limit is approximately about 7.8 MW. There is a large drop in the value of the heat release rate at the beginning of the burning duration due to the complete burning of the thinner portions of the fuel loads. The high value of the heat release rate is based on the exposure of the surface area of a certain fuel load, such as the carpet initially. After the large drop, the values of heat release rate decrease according to the burning of the thicker portions of the fuel loads inside the bedroom. The thicker the fuel, the longer it takes to complete the burning.

The fire load density for this bedroom is approximately about 750 MJ/m^2. Although this value shows that the amount of the fuel load inside the bedroom is quite high, one would expect to see a higher portion of heat release curve predicted beyond the ventilation limit. This is due to the quantities of the burning fuel exceeding the available ventilation, which is needed to support the burning.

However, as seen in Figure 8.3.4.2, the result obtained is not as expected. This is because the outcome of the value of the heat release rate is based on the total amount of the exposed surface areas of the fuel loads to the fire, and not the total amount of the fuel loads (in kg) stored inside the bedroom, as considered in previous surveys. As most of the furniture inside the bedroom is stacked closely together, this reduced the possibility of more surfaces of each fuel being exposed to the fire, which in turn reduced the value of the heat release rate. Besides that, the bedroom also has high ventilation.

Consequently, this means that the lesser the surface area exposed to the fire, the lower the value of the heat release rate.

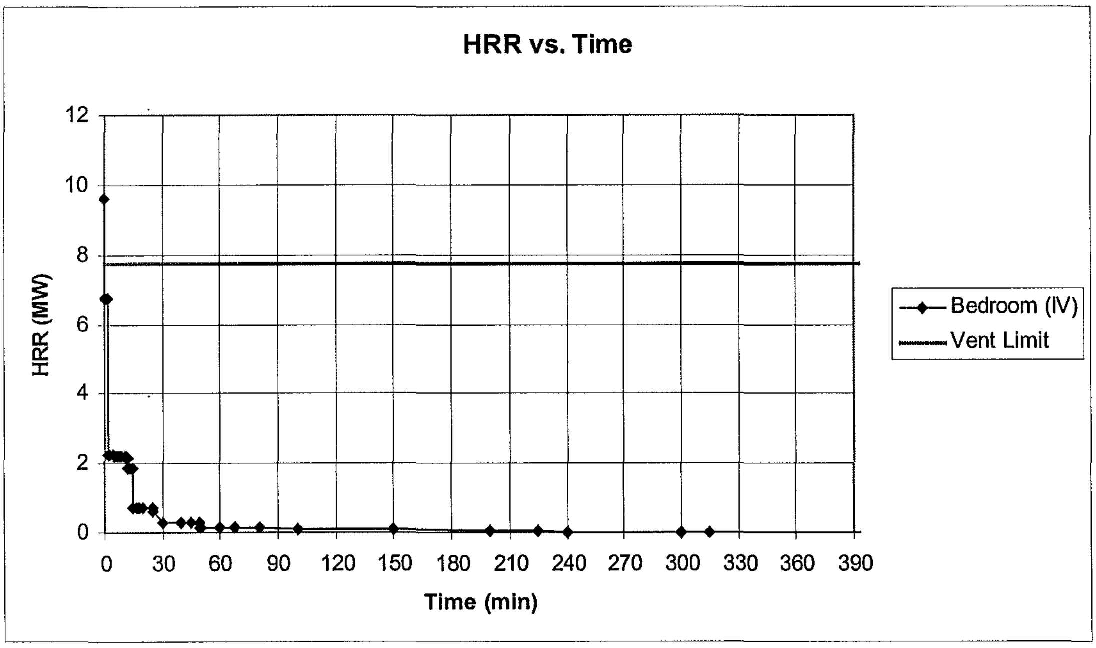


Figure 8.3.4.2: HRR vs. Time graph for fuel load inside Bedroom (IV).

The behaviour of the figure above, for option (a), indicates that during the post-flashover fire, due to the limited air supply to support the burning, some of the fuel is going to burn outside the room. This is showed by the heat release curve, which is beyond the ventilation limit, shown in Figure 8.3.4.2 above. This portion of the energy release is given off mostly by the burning of the thinner portion of the fuel, with large surfaces exposed to the fire initially at flashover.

Figure 8.3.4.3 shows the concept described for option (b). As before, the amount of heat release rate beyond the ventilation limit (E1) is shifted downward, under the ventilation limit, and the original amount energy under the ventilation limit (E2) is shifted to the right side of E1.

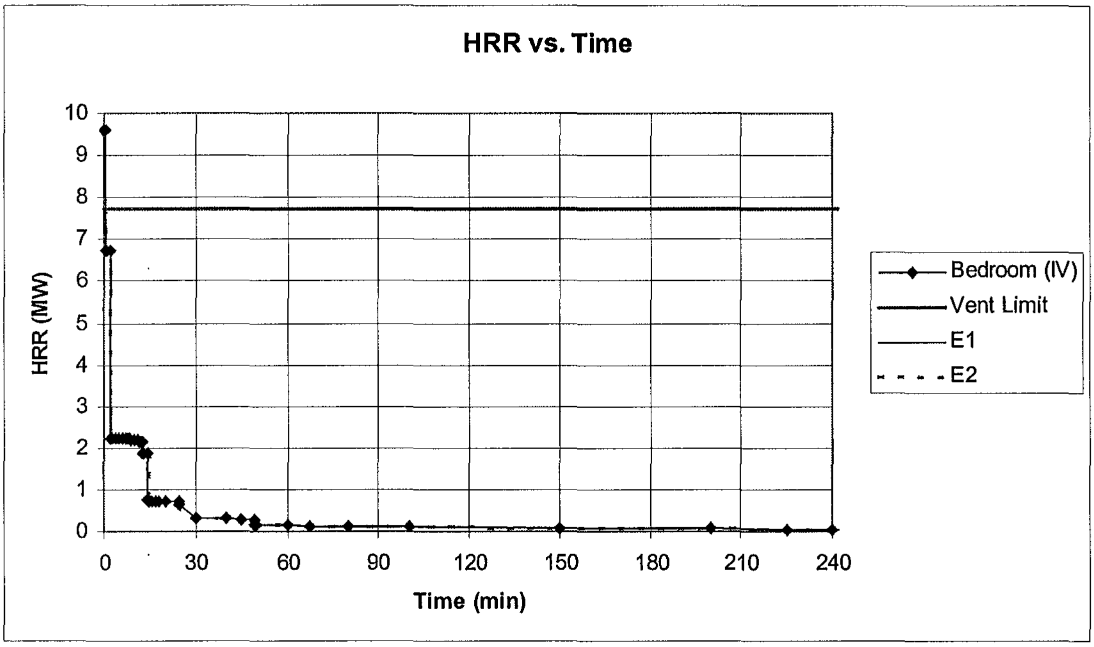


Figure 8.3.4.3:HRR vs. Time graph showing the shifting of E1 and E2 under the ventilation limit for Bedroom (IV).

The shifting of the heat release rate curve after dividing the original curve into E1 and E2 is extremely small. The trend of E1 and E2 shown in Figure 8.3.4.3 indicates that E1, which is nearer to the window, will be burned first before the burning of the fuel loads E2, which are further away from the window.

8.4 Academy Motel

8.4.1 Bedroom

The bedroom of the motel has a dimension of 3.63 m x 3.08 m. It has a small opening to the outside air with a dimension of approximately 0.98 m x 2 m. The glass on the opening to the outside air is assumed to be broken during the post-flashover fire. Although the bedroom has a door with a dimension of approximately 0.9 m x 2 m, it is not considered to be a source of ventilation and is considered to be in the closed position during the modelling.

Table 8.4.1.1 below shows the summary descriptions of each item inside the bedroom, with the exposed surface areas of each item carefully assessed.

Fire Load	Type	Quantity	Dimensions (m)	Mass (kg) (approx.)	Surface Area Exposed
Fixed					
Door + frame	W	1	0.89 x 2 x 0.015	16 ea	Exposed from inside the compartment
Carpet	P	1	3.63 x 3.08	25 ea	Exposed from upper face
Moveable					
Contents inside cupboard	P	1	0.8 x 1	20 ea	Exposed from upper and side faces
Bed ~ single	P + W + S	1	1.88 x 0.9	90 ea	Exposed from upper and side faces
Bed ~ double	P + W + S	1	1.88 x 1.5	120 ea	Exposed from upper and side faces
Cupboard (empty)	W	1	0.48 x 0.44 x 0.59 with thickness 0.02	10 ea	All faces except back
Curtain	P	1	0.98 x 2	2 ea	Exposed from front and side faces

** N/A ~ steel materials are considered to be low fuel load in fire. Thus, surfaces are not involved in the fire.*

W = Wood, P = Plastic, S = Steel, E = Electrical, G = Glass.

Table 8.4.1.1: Summary descriptions of each fuel load in motel (bedroom).

Figure 8.4.1.1 shows the layout of motel (bedroom).

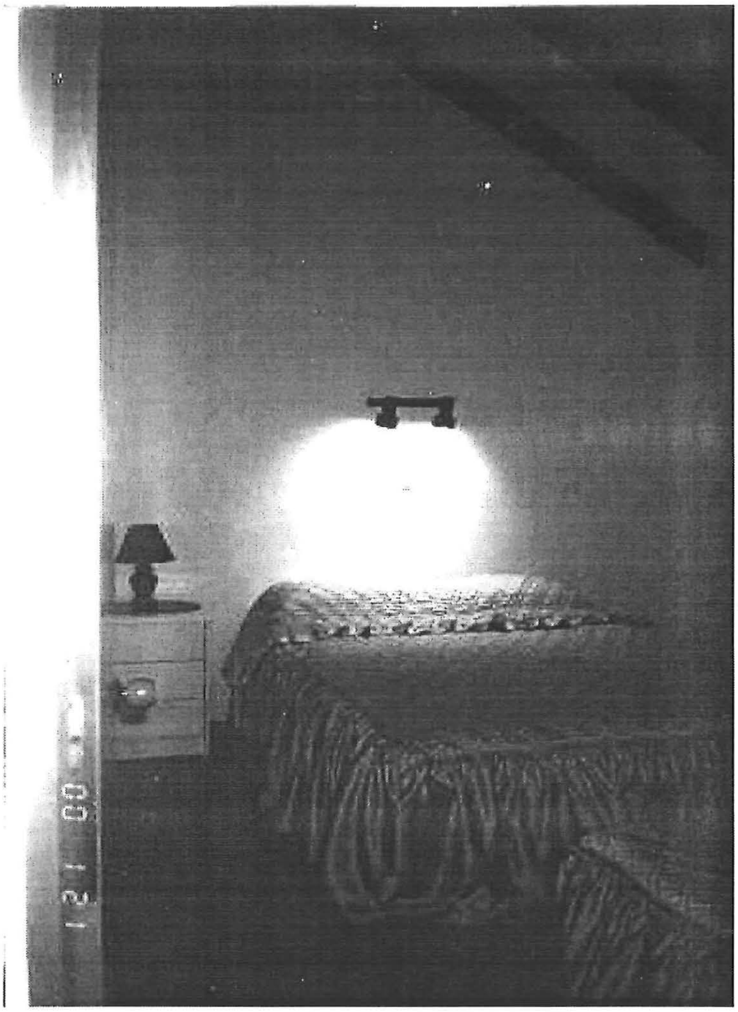


Figure 8.4.1.1: Layout of motel (bedroom).

Figure 8.4.1.2 below shows the total amount of heat release rate available inside the room. The maximum value of the heat release rate is approximately 12 MW, based on the total exposed surface area of the fuel loads during a post-flashover fire. The ventilation limit is approximately 4.3 MW. There is a large drop in the value of the heat release rate at the beginning of the burning duration due to the complete burning of the thinner portions of the fuel loads. The high value of the heat release rate is based on the exposed surface area of the fuel loads. After the large drop, the values of heat release rate decrease according to the burning of the thicker portions of the fuel loads inside the room.

Figure below indicates more fuel being burnt beyond the ventilation limit as more surfaces of the fuel loads is being exposed to the fire. The larger the exposed surface area, the higher the value of the heat release rate.

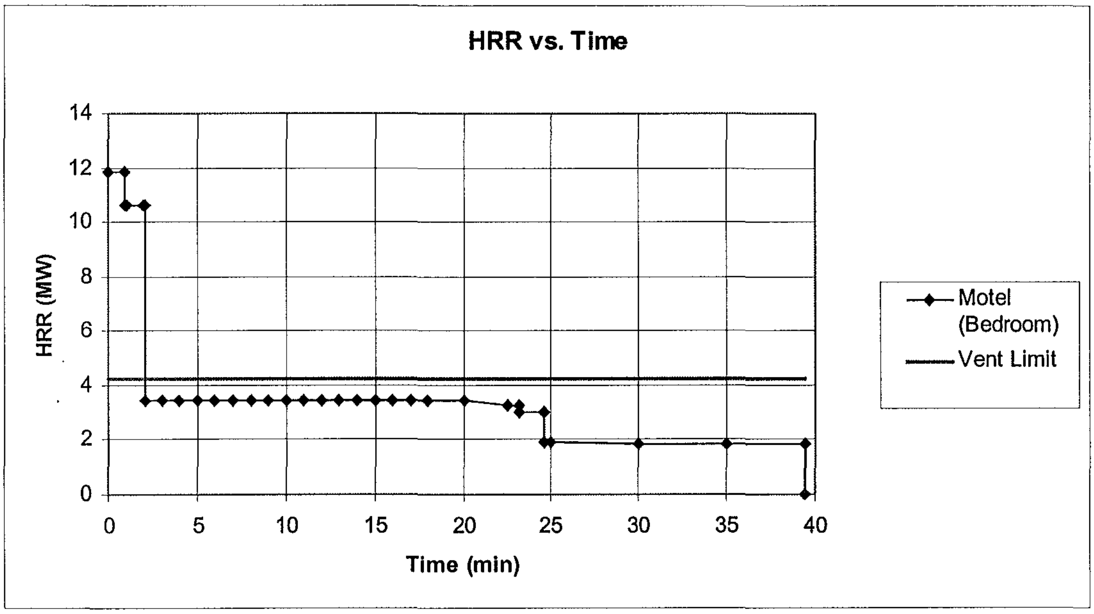


Figure 8.4.1.2: HRR vs. Time graph for fuel load inside motel (bedroom).

For option (a), Figure 8.4.1.2 above indicates that during the post-flashover fire, due to the limited air supply to support the burning, some fuel is going to burn outside the room. This is showed by the heat release curve, which is beyond the ventilation limit. This portion of the energy release is given off mostly by the burning of the thinner portion of the fuel, with their surfaces exposed to fire.

Figure 8.4.1.3 shows the concept described for option (b). As before, the amount of heat release rate beyond the ventilation limit (E1) is shifted downward, under the ventilation limit, and the original amount energy under the ventilation limit (E2) is shifted to the right side of E1.

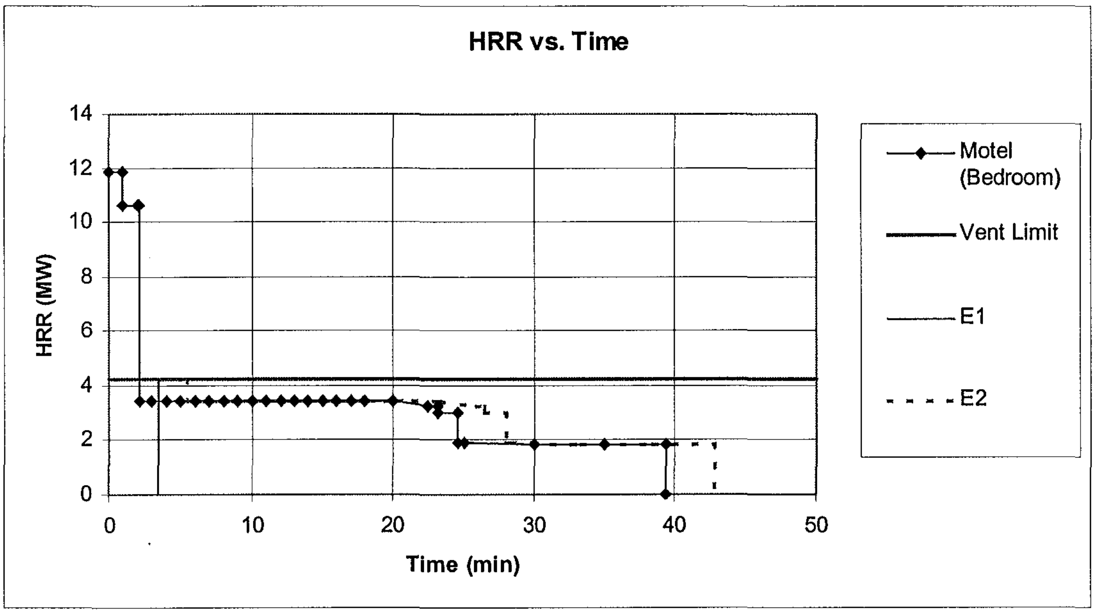


Figure 8.4.1.3:HRR vs. Time graph showing the shifting of E1 and E2 under the ventilation limit for motel (bedroom).

By shifting and dividing the original curve into E1 and E2, the heat release rate curve will shift by only 3 minutes. The trend of E1 and E2 shown in Figure 8.4.1.3 indicates that E1, which is nearer to the window, will be burned first before the burning of the fuel loads E2, which are further away from the window takes place.

8.4.2 Kitchen + Living Room

This part of the motel has a dimension of approximately 6 m x 3.9 m. It has a few ventilation openings to the outside air with dimensions ranging from 0.46 m width to 1.98 m height. All the glass on the openings is assumed to be broken during the post-flashover fire. Although the area has two doors with a dimension of approximately 0.9 m x 2 m each, these are not considered to be a source of ventilation and these doors are considered to be in the closed position during the modelling.

The room contains all sorts of fuel load ranging from wood materials to plastic materials, which are assumed to be ignited all at once during a post-flashover fire. The mass, dimensions and the exposed surface areas of each item are carefully assessed. Table 8.4.2.1 below shows the summary descriptions of each item.

Fire Load	Type	Quantity	Dimensions (m)	Mass (kg) (approx.)	Surface Area Exposed
Fixed					
Carpet	P	1	6.03 x 3.9	53 ea	Exposed from upper face
Door + frame	W	2	0.89 x 2 x 0.015	16 ea	Exposed from inside the compartment
Built-in cupboard a	W	1	1.5 x 0.74 x 0.9 with thickness 0.02	30 ea	All faces except back
Built-in cupboard b	W	1	1.16 x 0.74 x 0.9 with thickness 0.03	30 ea	All faces except back
Built-in cupboard c	W	1	1.2 x 0.32 x 0.6 with thickness 0.04	15 ea	All faces except back
Moveable					
Couch	P + W	1	1.95 x 0.9	40 ea	Exposed from upper and side faces
Chair	P + S	4	0.51 x 0.44	7 ea	Exposed from upper and side faces
Table	W + S	1	diameter = 1.19	30 ea	Exposed from upper and side faces
Bed ~ single	P + W + S	1	1.88 x 0.9	90 ea	Exposed from upper and side faces
TV and cabinet	P + W + S + G	1	0.59 x 0.37	20 ea	Exposed from upper and side faces
Telephone	P + S + E	1	0.165 x 0.225	1 ea	Exposed from upper and side faces
Curtain	P	1	1.96 x 1.11	0.5 ea	Exposed from front and side faces
		1	0.46 x 1.11	0.5 ea	Exposed from front and side faces
		1	2.36 x 1.98	1 ea	Exposed from front and side faces
Pictures	W	1	0.82 x 0.57 x 0.02	4 ea	All faces except back
Pillow	P	5	0.36 x 0.36	1 ea	Exposed from upper and side faces
Other plastic things	P	1	0.19 x 0.52	3 ea	Exposed from upper and side faces

** N/A ~ steel materials are considered to be low fuel load in fire. Thus, surfaces are not involved in the fire.*

W = Wood, P = Plastic, S = Steel, E = Electrical, G = Glass.

Table 8.4.2.1: Summary descriptions of each fuel load in motel (kitchen + living room).

During the modelling for each item available inside this room, besides the thinner portion of the cellulosic materials, it is found that non-cellulosic materials will have a shorter burning period than the thicker portion of the cellulosic materials.

Figure 8.4.2.1 shows the layout of motel (kitchen + living room).

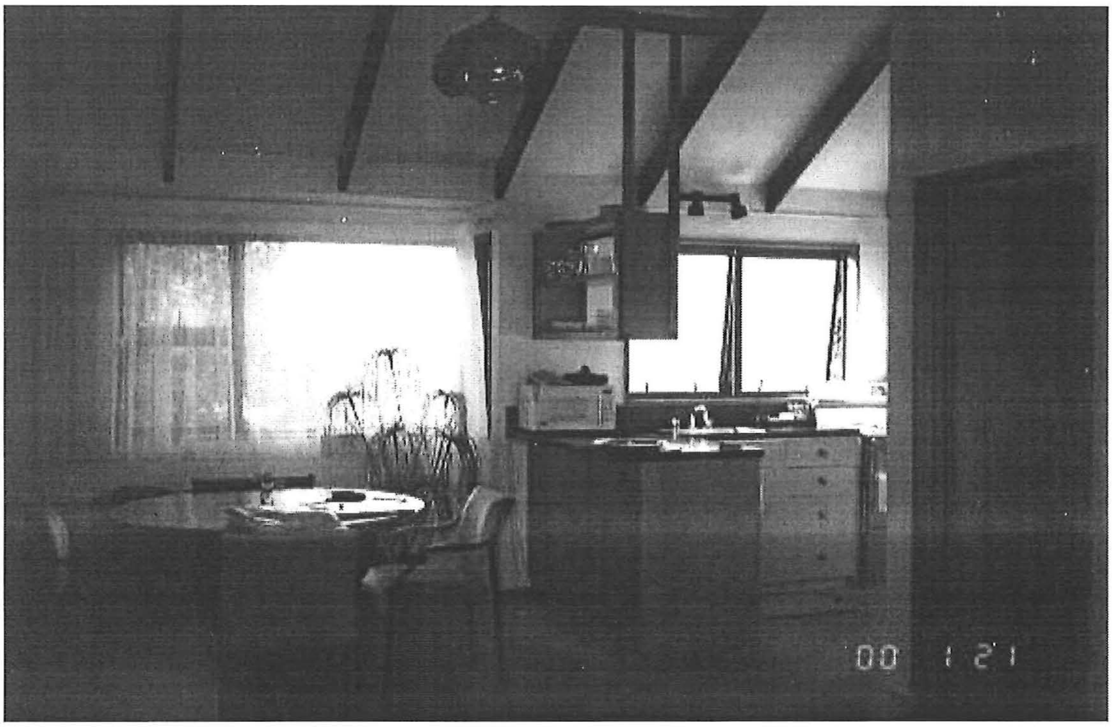


Figure 8.4.2.1: Layout of motel (kitchen + living room).

Figure 8.4.2.2 below shows the total amount of heat release rate available inside the compartment. The maximum value of the heat release rate is approximately 24.6 MW, based on the total exposed surface area of the fuel loads during a post-flashover fire. The ventilation limit is about 17 MW. Each drop in the value of the heat release rate represents the complete burning of the thinner portions of the fuel loads. The larger the exposed surface areas to the fire, the higher the value of the heat release rate. The duration of burning is determined by the thickest part of the fuel load.

The fire load density for this compartment is only about 350 MJ/m^2. However, due to massive exposed area of the fuel to the fire, the value of the heat release rate is quite high, as seen in Figure 8.4.2.2.

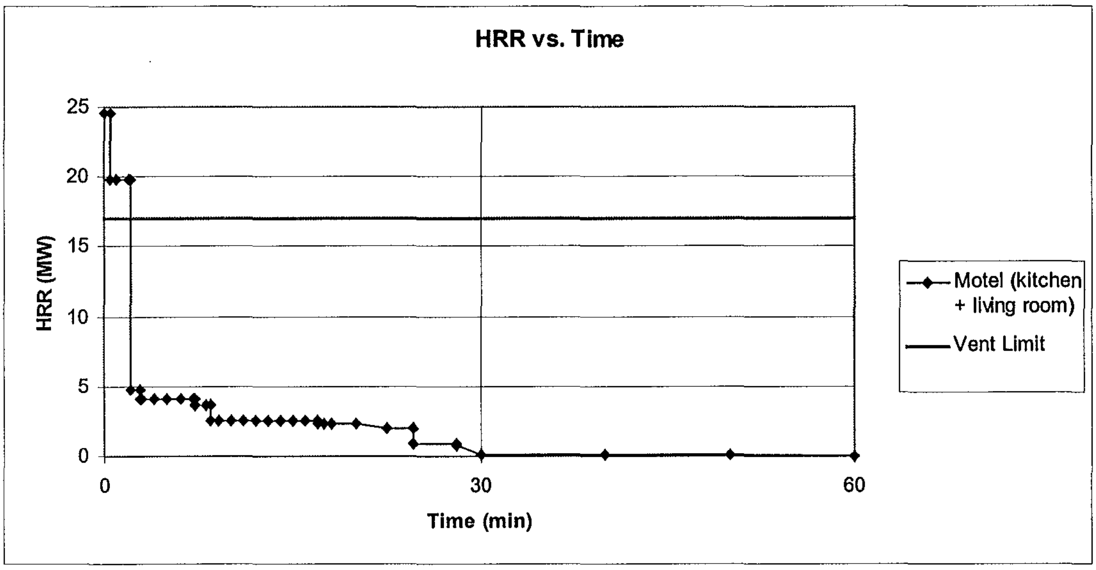


Figure 8.4.2.2: HRR vs. Time graph for fuel load inside motel (kitchen + living room).

In order to explain the behaviour of the figure above, option (a) indicates that during the post-flashover fire, due to the limited air supply to support the burning, some fuel is going to burn outside the room. This is showed by the heat release curve, which is beyond the ventilation limit. This portion of the energy release is given off mostly by the burning of the thinner portion of the fuel, with their surfaces exposed to fire.

Figure 8.4.2.3 shows the concept described for option (b). As before, the amount of heat release rate beyond the ventilation limit (E1) is shifted downward, under the ventilation limit, and the original amount energy under the ventilation limit (E2) is shifted to the right side of E1.

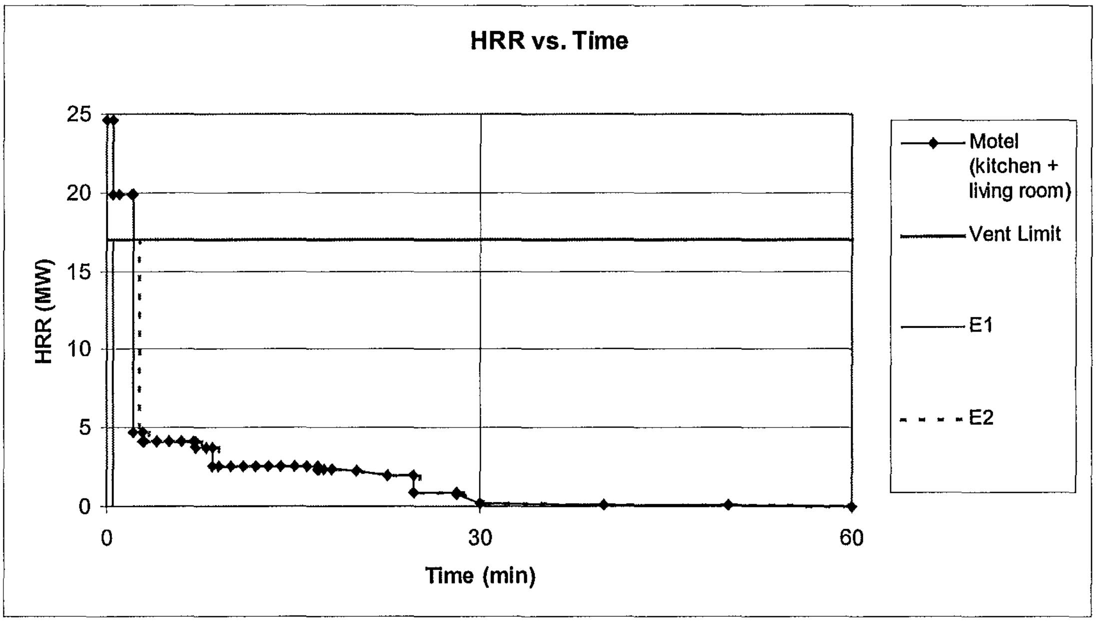


Figure 8.4.2.3:HRR vs. Time graph showing the shifting of E1 and E2 under the ventilation limit for motel (kitchen + living room)

The shifting of the original curve is very small. The trend of E1 and E2 shown in Figure 8.4.2.3 indicates that E1, which is nearer to the window, will be burned first before the burning of the fuel loads E2, which are further away from the window.

8.5 Conclusions of the Results

Therefore, by looking at all the results obtained above, it can be seen that the exposed surface area of the fuel to the fire is indeed has a great impact on the outcome of the value of the heat release rate. The larger the exposed surface area of the fuel, the higher the value of the heat release rate. It must be noted that the outcomes of the heat release rate presented above is entirely based on how much surface area of the fuel is exposed to the fire and not the quantity of the fuel load inside the fire compartment.

In order to describe the burning behaviour based on the total exposed surface area of the fuel loads inside each surveyed room, as mentioned earlier, two option proposed have been used.

However, by careful analysis of all the above results, it is found that the burning behaviour of the fuel loads based on the total surface area exposed to the fire is not exactly option (a) or option (b).

This is because the energy release beyond the ventilation limit is mostly given off by the thinner parts of the fuel loads based on the surface area exposed to the fire. Therefore, these parts might be long gone inside the fire compartment before the air supply becomes limited to support the burning. Option (b) again does not exactly represent the true behaviour of burning based on the surface area exposed to the fire. This is because although the concept of the fuel nearer to the ventilation being burned first is acceptable, the fuel further away from the ventilation might be pyrolyzing, if not burning. This is especially true for thin fuel such as pieces of paper lying around inside the compartment.

Therefore, it is assumed that based on the exposed surface area of the fuel, the real situation of the energy release inside each surveyed room might be between E1 and E2, where besides the burning of the fuel loads nearer to the ventilation, the thinner fuel loads further away from the ventilation might also be burnt or else undergoing a pyrolyzing process.

8.6 Comparisons with Previous Data

Table 8.5.1 below shows the value of the fire load density inside each surveyed building occupancy. The value of the fire load in kg wood equivalent per m^2 is obtained by dividing the fire load density by 16.7 MJ/kg (net calorific value of wood).

Room	Room Area (m^2)	Energy Released (MJ)	Fire Load Density (MJ/m^2)	Fire Load (in kg wood equivalent / m^2)
Postgraduate Offices:				
E306	16.6	15020	904	54
E312	36.2	14870	411	25
E313	16.6	13200	795	48
E328	16.6	13300	801	48
Mean			728	44
University Rooms:				
Andy's office	17.0	20000	1179	71
Catherine's office	18.3	11900	651	39
Charley's office	16.9	38000	2247	135
Civil Eng. computer room	216	85600	395	24
Civil Eng. meeting room	119	12050	102	6
Civil Eng. store room	14.8	35000	2366	142
Mean			1157	69
Flat - Bedroom:				
Bedroom (I)	8.9	5278	594	36
Bedroom (II)	7.9	5565	705	42
Bedroom (III)	13.5	11516	852	51
Bedroom (IV)	6.7	4960	746	45
Mean			724	43
Motel:				
Motel (bedroom)	11.2	8459	757	45
Motel (kitchen + living room)	23.5	8178	348	21
Mean			552	33

Table 8.5.1: Summarized results of floor areas and total fire loads for each surveyed building occupancy.

A summary of the mean value of fire load comparisons between this survey and previous data is shown in Table 8.5.2.

Building Occupancy	Surveyed		Table 2.4.1 (Robertson & Gross, 1970)		Table 2.4.11 (Barnett, 1984)		Table 2.4.14 (Narayanan, 1994)	
	(kg/m^2)	(MJ/m^2)	(kg/m^2)	(MJ/m^2)	(kg/m^2)	(MJ/m^2)	(kg/m^2)	(MJ/m^2)
Offices	57	950	35 - 212	585 - 3540	22	436	37.8	681
Residence (bedroom)	43	724	40 - 69	668 - 1152		-		-
Motel	33	552		-		-		-

Table 8.5.2: Summary of the mean value of the total fire load comparisons.

From Table 8.5.2, it can be seen that the surveyed results are in the range of the values given in Table 2.4.1 (Robertson and Gross, 1970) for both offices and residential building occupancy. However, the surveyed results are overestimated when compared to data given in Table 2.4.11 (Barnett, 1984) and Table 2.4.14 (Narayanan, 1994) for offices. This may be due to that the preliminary survey done by Barnett (1984) is based on one sample only, and furthermore the different type of offices being surveyed might also have influenced the results. Besides that, the different sampling and survey techniques used could also have an impact on the results.

It is also needs to be noted that the higher value of the surveyed results may also be due to the fact that during the modelling, especially for the plastic materials, the value of the density and the net calorific value is based either on polyurethane or polypropylene material. Hence, for future surveys, in order to be able to predict accurate results, a suitable value of density and the net calorific value must be chosen for each type of plastic material.

When comparing the surveyed results with data in Table 2.4.2 (Babrauskas, 1976), it can be seen that the cumulative probability of fire loads for the surveyed results of offices is between 80 and 99 per cent. For residences (flats), the cumulative probability of fire loads for the surveyed results is between 50 and 80 per cent.

Unfortunately, there were no data found (during the period of the preparation of this report) for the comparison of the total fuel load in motels.

However, it can be concluded that the method used for this survey to obtain the total fuel load, which is based on the exposed surface area of the fuel load in a certain type of building occupancy, proved to produce reasonable results.

9. CONCLUSIONS & RECOMMENDATIONS

9.1 Conclusions

This report investigated the effect of surface area and thickness on fire loads. A new method was developed for measuring cellulosic fuel loads by considering the exposed surface area and the thickness, as well as the mass of combustible materials.

For each fuel item, the value of the heat release rate is calculated, assuming a constant regression rate on all exposed surfaces, simulating a post-flashover fire. Based on the methodology developed, it was found that the heat release rate is a function of the surface area, while the duration of burning is a function of the thickness of the fuel.

A survey was carried out on typical items of furniture, in order to find the total fire load in each item. From this, the value of the heat release rate based on the surface area exposed to the fire was predicted. The survey was extended to enclosed compartments in typical buildings, including residential, motel and university rooms. For each compartment, the surface controlled heat release rate was compared with the ventilation controlled heat release rate. For most compartments, the predicted surface controlled heat release rate was very high at flashover, but the value of the heat release rate dropped rapidly as the thin exposed fuel items were burned away. The predicted duration of burning of thick item of fuel was several hours, without any intervention.

9.2 Recommendations

On the basis of the findings of this report, the following recommendations are made for the future study of burning behaviour based on the effect of the surface area and thickness of the fuel loads:

- more fire load surveys to be conducted, especially on other types of building occupancies.

- more detailed surveys to be conducted on other item of furniture, especially in predicting the amount of surface area exposed.
- better models for plastic materials to be developed, as the value of the heat release rate based on the exposed surface area of the fuel load is underestimated by the current proposed model.
- more accurate values of density and net calorific value for each plastic material to be obtained, in order to predict more accurate results.

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APPENDICES

Appendix A: Fire Load Energy Densities

This Appendix is extracted from CIB (1986). The table gives average fire load densities using data from Switzerland.

The following values for *fire load densities* (only variable fire load densities) are taken from *Beilage 1:Brandschutztechnische Merkmale verschiedener Nutzungen und Lagerguter* and are defined as density per unit floor area (MJ/m^2).

Note that for the determination of the variable fire load of storage areas, the values given in the following table have to be multiplied by the height of storage in metres. Areas and aisles for transportation have been taken into consideration in an averaging manner.

The values are based on a large investigation carried out during the years 1967-1969 by a staff of 10-20 students under the guidance of the Swiss Fire Prevention Association for Industry and Trade (Brandverhutungsdienst fur Industrie und Gewerbe, Nuschelerstrasse 45, CH-8001 Zurich), with the financial support of the governmental civil defence organisation.

For each type of occupancy, storage and/or building, a minimum of 10-15 samples were analysed; normally, 20 or more samples were available. All values given in the following pages are average values. Unfortunately, it has been impossible to obtain the basic data sheets of this investigation. In order to estimate the corresponding standard deviations and the 80%-90%- and 95%-fractile values, the data from this source were compared with data given in refs 1-5,7-11. This comparison results in the following suggestions.

(a) For well-defined occupancies which are rather similar or with very limited differences in furniture and stored goods, eg dwellings, hotels, hospitals, offices and schools, the following estimates may suffice:

Coefficient of variation	=	30%-50% of the given average value
90%-fractile value	=	(1.35-1.65) x average value
80%-fractile value	=	(1.25-1.50) x average value
isolated peak values	=	2 x average value

(b) For occupancies which are rather dissimilar or with larger differences in furniture and stored goods, eg shopping centres, department stores and industrial occupancies, the following estimates are tentatively suggested:

Coefficient of variation	=	50%-80% of the given average value
90%-fractile value	=	(1.65-2.0) x average value
80%-fractile value	=	(1.45-1.75) x average value
isolated peak values	=	2.5 x average value

Type of occupancies	Fabrication MJ/m^2	Storage MJ/m^2/m
Academy	300	
Accumulator forwarding	800	
Accumulator mfg	400	800
Acetylene cylinder storage	700	
Acid plant	80	
Adhesive mfg	1000	3400
Administration	800	
Adsorbent plant for combustible vapours	>1700	
Aircraft hangar	200	
Airplane factory	200	
Aluminium mfg	40	
Aluminium processing	200	
Ammunition mfg	Special	
Animal food preparing, mfg	2000	3300
Antique shop	700	
Apparatus forwarding	700	
Apparatus mfg	400	
Apparatus repair	600	
Apparatus testing	200	
Arms mfg	300	
Arms sales	300	
Artificial flower mfg	300	200
Artificial leather mfg	1000	1700
Artificial leather processing	300	
Artificial silk mfg	300	1100
Artificial silk processing	210	
Artificial stone mfg	40	
Asylum	400	
Authority office	800	
Awning mfg	300	1000
Bag mfg (jute, paper, plastic)	500	
Bakery	200	
Bakery, sales	300	
Ball bearing mfg	200	
Bandage mfg	400	
Bank, counters	300	
Bank, offices	800	
Barrel mfg, wood	1000	800
Basement, dwellings	900	
Basketware mfg	300	200
Bed sheeting production	500	1000
Bedding plant	600	
Bedding shop	500	
Beer mfg (brewery)	80	
Beverage mfg, nonalcoholic	80	
Bicycle assembly	200	400
Biscuit factories	200	
Biscuit mfg	200	
Bitumen preparation	800	3400
Blind mfg, venetian	800	300
Blueprinting firm	400	
Boarding school	300	
Boat mfg	600	
Boiler house	200	
Bookbinding	1000	
Bookstore	1000	
Box mfg	1000	600
Brick plant, burning	40	
Brick plant, clay preparation	40	
Brick plant, drying kiln with metal grates	40	
Brick plant, drying kiln with wooden grates	1000	
Brick plant, drying room with metal grates	40	
Brick plant, drying room with wooden grates	400	
Brick plant, pressing	200	
Briquette factories	1600	
Broom mfg	700	400
Brush mfg	700	800
Butter mfg	700	4000
Cabinet making (without woodyard)	600	
Cable mfg	300	600
Cafe	400	
Camera mfg	300	
Candle mfg	1300	22400
Candy mfg	400	1500
Candy packing	800	
Candy shop	400	
Cane products mfg	400	200
Canteen	300	
Car accessory sales	300	
Car assembly plant	300	
Car body repairing	150	
Car paint shop	500	
Car repair shop	300	
Car seat cover shop	700	
Cardboard box mfg	800	2500
Cardboard mfg	300	4200
Cardboard products mfg	800	2500
Carpenter shed	700	
Carpet dyeing	500	
Carpet mfg	600	1700
Carpet store	800	
Cartwright's shop	500	
Cast iron foundry	400	800
Celluloid mfg	800	3400
Cement mfg	1000	
Cement plant	40	
Cement products mfg	80	
Cheese factory	120	
Cheese mfg (in boxes)	170	
Cheese store	100	
Chemical plants (rough average)	300	100
Chemist's shop	1000	
Children's home	400	
China mfg	200	
Chipboard finishing	800	
Chipboard pressing	100	
Chocolate factory, intermediate storage	6000	
Chocolate factory, packing	500	
Chocolate factory, tumbling treatment	1000	
Chocolate factory, all other specialities	500	

Type of occupancies	Fabrication MJ/m²	Storage MJ/m²/m
Church	200	
Cider mfg (without crate storage)	200	
Cigarette plant	3000	
Cinema	300	
Clay, preparing	50	
Cloakroom, metal wardrobe	80	
Cloakroom, wooden wardrobe	400	
Cloth mfg	400	
Clothing plant	500	
Clothing store	600	
Coal bunker	2500	
Coal cellar	10500	
Cocoa processing	800	
Coffee extract mfg	300	
Coffee roasting	400	
Cold storage	2000	
Composing room	400	
Concrete products mfg	100	
Condiment mfg	50	
Congress hall	600	
Contractors	500	
Cooking stove mfg	600	
Coopering	600	
Cordage plant	300	600
Cordage store	500	
Cork products mfg	500	800
Cosmetic mfg	300	500
Cotton mills	1200	
Cotton wool mfg	300	
Cover mfg	500	
Cutlery mfg (household)	200	
Cutting-up shop, leather, artificial leather	300	
Cutting-up shop, textiles	500	
Cutting-up shop, wood	700	
Dairy	200	
Data processing	400	
Decoration studio	1200	2000
Dental surgeon's laboratory	300	
Dentist's office	200	
Department store	400	
Distilling plant, combustible materials	200	
Distilling plant, incombustible materials	50	
Doctor's office	200	
Door mfg, wood	800	1800
Dressing, textiles	200	
Dressing, paper	700	
Dressmaking shop	300	
Dry-cell battery	400	600
Dry cleaning	300	
Dyeing plant	500	
Edible fat forwarding	900	
Edible fat mfg	1000	18900
Electric appliance mfg	400	
Electric appliance repair	500	
Electric motor mfg	300	
Electrical repair shop	600	

Type of occupancies	Fabrication MJ/m²	Storage MJ/m²/m
Electrical supply storage H< 3 m	1200	
Electro industry	600	
Electronic device mfg	400	
Electronic device repair	500	
Embroidery	300	
Etching plant glass/metal	200	
Exhibition hall, cars including decoration	200	
Exhibition hall, furniture including decoration	500	
Exhibition hall, machines including decoration	80	
Exhibition of paintings including decoration	200	
Explosive industry	4000	
Fertiliser mfg	200	200
Filling plant/barrels		
liquid filled and/or barrels incombustible	<200	
liquid filled and/or barrels combustible:		
Risk Class I	>3400	
Risk Class II	>3400	
Risk Class III	>3400	
Risk Class IV	>3400	
Risk Class V (if higher, take into consideration combustibility of barrels)	>1700	
Filling plant/small casks:		
liquid filled and casks incombustible	<200	
liquid filled and/or casks combustible:		
Risk Class I	<500	
Risk Class II	<500	
Risk Class III	<500	
Risk Class IV	<500	
Risk Class V (if higher, take into consideration combustibility of casks)	<500	
Finishing plant, paper	500	
Finishing plant, textile	300	
Fireworks mfg	Spez	2000
Flat	300	
Floor covering mfg	500	6000
Floor covering store	1000	
Flooring plaster mfg	600	
Flour products	800	
Flower sales	80	
Fluorescent tube mfg	300	
Foamed plastics fabrication	3000	2500
Foamed plastics processing	600	800
Food forwarding	1000	
Food store	700	
Forge	80	
Forwarding, appliances partly made of plastic	700	
Forwarding, beverage	300	
Forwarding, cardboard goods	600	

Type of occupancies	Fabrication MJ/m^2	Storage $MJ/m^2/m$
Forwarding, food	1000	
Forwarding, furniture	600	
Forwarding, glassware	700	
Forwarding, plastic products	1000	
Forwarding, printed matters	1700	
Forwarding, textiles	600	
Forwarding, tinware	200	
Forwarding, varnish, polish	1300	
Forwarding, woodware (small)	600	
Foundry (metal)	40	
Fur, sewing	400	
Fur store	200	
Furniture exhibition	500	
Furniture mfg (wood)	600	
Furniture polishing	500	
Furniture store	400	
Furrier	500	
Galvanic station	200	
Gambling place	150	
Glass blowing plant	200	
Glass factory	100	
Glass mfg	100	
Glass painting	300	
Glass processing	200	
Glassware mfg	200	
Glassware store	200	
Glazier's workshop	700	
Gold plating (of metals)	800	3400
Goldsmith's workshop	200	
Grainmill, without storage	400	13000
Gravestone carving	50	
Graphic workshop	1000	
Greengrocer's shop	200	
Hairdressing shop	300	
Hardening plant	400	
Hardware mfg	200	
Hardware store	300	
Hat mfg	500	
Hat store	500	
Heating equipment room, wood or coal-firing	300	
Heat sealing of plastics	800	
High-rise office building	800	
Homes	500	
Homes for aged	400	
Hosiery mfg	300	1000
Hospital	300	
Hotel	300	
Household appliances, mfg	300	200
Household appliances, sales	300	
Ice cream plant (including packaging)	100	
Incandescent lamp plant	40	
Injection moulded parts mfg (metal)	80	
Injection moulded parts mfg (plastic)	500	
Institution building	500	
Ironing	500	

Type of occupancies	Fabrication MJ/m^2	Storage $MJ/m^2/m$
Jewellery mfg	200	
Jewellery shop	300	
Joinery	700	
Joiners (machine room)	500	
Joiners (workbench)	700	
Jute, weaving	400	1300
Laboratory, bacteriological	200	
Laboratory, chemical	500	
Laboratory, electric, electronic	200	
Laboratory, metallurgical	200	
Laboratory, physics	200	
Lacquer forwarding	1000	
Lacquer mfg	500	2500
Large metal constructions	80	
Lathe shop	600	
Laundry	200	
Leather goods sales	700	
Leather product mfg	500	
Leather, tanning, dressing, etc	400	
Library	2000	2000
Lingerie mfg	400	
Liqueur mfg	400	800
Liquor mfg	500	800
Liquor store	700	
Loading ramp, including goods (rough average)	800	
Lumber room for miscellaneous goods	500	
Machinery mfg	200	
Match plant	300	800
Mattress mfg	500	500
Meat shop	50	
Mechanical workshop	200	
Metal goods mfg	200	
Metal grinding	80	
Metal working (general)	200	
Milk, condensed, evaporated mfg	200	9000
Milk, powdered, mfg	200	10500
Milling work, metal	200	
Mirror mfg	100	
Motion picture studio	300	
Motorcycle assembly	300	
Museum	300	
Musical instrument sales	281	
News stand	1300	
Nitrocellulose mfg	Spez	1100
Nuclear research	2100	
Nursery school	300	
Office, business	800	
Office, engineering	600	
Office furniture	700	
Office, machinery mfg	300	
Office machine sales	300	
Oilcloth mfg	700	1300
Oilcloth processing	700	2100
Optical instrument mfg	200	200

Type of occupancies	Fabrication MJ/m^2	Storage MJ/m^2/m
Packing, food	800	
Packing, incombustible goods	400	
Packing material, industry	1600	3000
Packing, printed matters	1700	
Packing, textiles	600	
Packing, all other combustible goods	600	
Paint and varnish, mfg	4200	
Paint and varnish, mixing plant	2000	
Paint and varnish shop	1000	
Painter's workshop	500	
Pain shop (cars, machines, etc)	200	
Paint shop (furniture, etc)	400	
Paper mfg	200	10000
Paper processing	800	1100
Parking building	200	
Parquetry mfg	2000	1200
Perambulator mfg	300	800
Perambulator shop	300	
Perfume sale	400	
Pharmaceutical mfg	300	800
Pharmaceuticals, packing	300	800
Pharmacy (including storage)	800	
Photographic laboratory	100	
Photographic store	300	
Photographic studio	300	
Picture frame mfg	300	
Plaster product mfg	80	
Plastic floor tile mfg	800	
Plastic mfg	2000	5900
Plastic processing	600	
Plastic products fabrication	600	
Plumber's workshop	100	
Plywood mfg	800	2900
Polish mfg	1700	
Post office	400	
Potato, flaked, mfg	200	
Pottery plant	200	
Power station	600	
Precious stonė, cutting etc	80	
Precision instrument mfg		
(containing plastic parts)	200	
(without plastic parts)	100	
Precision mechanics plant	200	
Pressing, metal	100	
Pressing, plastics, leather, etc	400	
Preparation briquette production		
Printing, composing room	300	
Printing, ink mfg	700	3000
Printing, machine hall	400	
Printing office	1000	
Radio and TV mfg	400	
Radio and TV sales	500	
Radio studio	300	
Railway car mfg	200	
Railway station	800	
Railway workshop	800	
Record player mfg	300	200
Record repository, documents see also storage	4200	
Refrigerator mfg	1000	300
Relay mfg	400	

Type of occupancies	Fabrication MJ/m^2	Storage MJ/m^2/m
Repair shop, general	400	
Restaurant	300	
Retouching department	300	
Rubber goods mfg	600	5000
Rubber goods store	800	
Rubber processing	600	5000
Saddlery mfg	300	
Safe mfg	80	
Salad oil forwarding	900	
Salad oil mfg	1000	18900
Sawmill (without woodyard)	400	
Scale mfg	400	
School	300	
Scrap recovery	800	
Seedstore	600	
Sewing machine mfg	300	
Sewing machine store	300	
Sheet mfg	100	
Shoe factory, forwarding	600	
Shoe factory, mfg	500	
Shoe polish mfg	800	2100
Shoe repair with manufacture	700	
Shoe store	500	
Shutter mfg	1000	
Silk spinning (natural silk)	300	
Silk weaving (natural silk)	300	
Silverwares	400	
Ski mfg	400	1700
Slaughter house	40	
Soap mfg	200	4200
Soda mfg	40	
Soldering	300	
Solvent distillation	200	
Spinning mill, excluding garnetting	300	
Sporting goods store	800	
Spray painting, metal goods	300	
Spray painting, wood products	500	
Stationery store	700	
Steel furniture mfg	300	
Stereotype plate mfg	200	
Stone masonry	40	
Storeroom (workshop storerooms etc)	1200	
Synthetic fibre mfg	400	
Synthetic fibre processing	400	
Synthetic resin mfg	3400	4200
Tar-coated paper mfg	1700	
Tar preparation	800	
Telephone apparatus mfg	400	200
Telephone exchange	80	
Telephone exchange mfg	100	
Test room, electric appliances	200	
Test room, machinery	100	
Test room, textiles	300	
Theatre	300	
Tin can mfg	100	
Tinned goods mfg	40	
Tinware mfg	120	
Tire mfg	700	1800
Tobacco products mfg	200	2100

Type of occupancies	Fabrication MJ/m^2	Storage MJ/m^2/m
Tobacco shop	500	
Tool mfg	200	
Toy mfg (combustible)	100	
Toy mfg (incombustible)	200	
Toy store	500	
Tractor mfg	300	
Transformer mfg	300	
Transformer winding	600	
Travel agency	400	
Turnery (wood working)	500	
Turning section	200	
TV studio	300	
Twisting shop	250	
Umbrella mfg	300	400
Umbrellas store	300	
Underground garage, private	>200	
Underground garage, public	<200	
Upholstering plant	500	
Vacation home	500	
Varnishing, appliances	80	
Varnishing, paper	80	
Vegetable, dehydrating	1000	400
Vehicle mfg, assembly	400	
Veneering	500	2900
Veneer mfg	800	4200
Vinegar mfg	80	100
Vulcanising plant (without storage)	1000	
Waffle mfg	300	1700
Warping department	250	
Washing agent mfg	300	200
Washing machine mfg	300	40
Watch assembling	300	40
Watch mechanism mfg	40	
Watch repair shop	300	
Watch sales	300	
Water closets	~0	
Wax products forwarding	2100	
Wax products mfg	1300	2100
Weaving mill (without carpets)	300	
Welding shop (metal)	80	
Winding room	400	
Winding, textile fibres	600	
Window glass mfg	700	
Window mfg (wood)	800	
Wine cellar	20	
Wine merchant's shop	200	
Wire drawing	80	
Wire factory	800	
Wood carving	700	
Wood drying plant	800	
Wood grinding	200	
Wood pattern making shop	600	
Wood preserving plant	3000	
Youth hostel	300	

Appendix B: Fire Load Data Entry Sheets

Building Occupancies:.................................... Date:......................

Room Length (m):.......... Room Width (m):.......... Total floor area (m^2) = ...					
Designation of Fixed Fire Load	Type	Quantity	Mass (kg)	Dimensions (m)	Surface Area Exposed (m^2)

P = Plastic W = Wood S = Steel G = Glass E = Electrical

Building Occupancies:................................... Date:.....................

Room Length (m):.......... Room Width (m):.......... Total floor area (m^2) = ...					
Designation of Moveable Fire Load	Type	Quantity	Mass (kg)	Dimensions (m)	Surface Area Exposed (m^2)

P = Plastic W = Wood S = Steel G = Glass E = Electrical

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